AFRL-HE-WP-TR-2000-0023

UNITED STATES AIR FORCE RESEARCH LABORATORY

REPRESENTING THE COGNITIVE DEMANDS OF NEW SYSTEMS: A DECISION-CENTERED DESIGN APPROACH

Patricia McDermott
Gary Klein
Marvin Thordsen

KLEIN ASSOCIATES INC.
1750 COMMERCE CENTER BLVD. NORTH
FAIRBORN, OH 45324

Steve Ransom
Michael Paley

APTIMA
600 W. CUMMINGS PARK, SUITE 3050
WOBURN, MA 01801

MARCH 2000

FINAL REPORT FOR THE PERIOD APRIL 1999 TO JANUARY 2000

Human Effectiveness Directorate
Crew System Interface Division
2255 H Street
Wright-Patterson AFB, OH 45433-7022

NOTICES

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Please do not request copies of this report from the Air Force Research Laboratory. Additional copies may be purchased from:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Federal Government agencies and their contractors registered with the Defense Technical Information Center should direct requests for copies of this report to:

Defense Technical Information Center
8725 John J. Kingman Road, Suite 0944
Ft. Belvoir, Virginia 22060-6218

DISCLAIMER

This Technical Report is published as received and has
Not been edited by the Air Force Research Laboratory,
Human Effectiveness Directorate.

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2000-0023

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

JOHN F. KENT, COL, USAF, BSC
Deputy Chief, Crew System Interface Division
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 2000	Final, April 1999 - January 2000

4. TITLE AND SUBTITLE

Representing the Cognitive Demands of New Systems: A Decision-Centered Design Approach

5. FUNDING NUMBERS

C: F41624-99-C-6029
PE: 65502F
PR: 3005
TA: HC
WU: 9F

6. AUTHOR(S)

* Patricia McDermott, Gary Klein, Marvin Thordsen,
**Steve Ransom, Michael Paley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

* Klein Associates Inc.
1750 Commerce Center Blvd. North
Fairborn, OH 45324

**Aptima
600 W. Cummings Park, Suite 3050
Woburn, MA 01801

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory, Human Effectiveness Directorate
Crew System Interface Division
Air Force Materiel Command
Wright-Patterson AFB OH 45433-7022

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFRL-HE-WP-TR-2000-0023

11. SUPPLEMENTARY NOTES

Air Force Project Manager: Dr. Edward A. Martin, AFRL/HECI

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited	

13. ABSTRACT *(Maximum 200 words)*

This report was developed under SBIR Contract for Topic No. AF99-089. As information technologies are becoming more central to weapons systems, the burden is shifting from conventional human factors requirements to the cognitive requirements. This report describes results of a Phase I SBIR to explore the feasibility of a tool to help Program Managers address the decision-making aspects of teams early in the design cycle. One outcome is the demonstration of a clear need for such a tool. Interviews with prospective users indicated that input about crew decision making would be valuable in developing the concept of operations and driving development of the system -- including training, design, function allocation, and staffing. The feasibility of collecting this information has been demonstrated in the Airborne Laser domain. Information about cognitive requirements was collected via observations and Cognitive Task Analysis interviews. A scenario illustrates events and decisions of a potential Airborne Laser mission. This type of scenario is the basis for a tool to conceptualize the dynamics and tradeoffs that involve cognitive tasks. The prototype tool that would be developed in a follow-on effort is called CRITERIA (Cognitive Requirements for Individuals and Teams: Evaluations, Recommendations, Inspection, and Analysis). The intent of CRITERIA is to define and represent the cognitive criteria for tasks in complex systems.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Decision-centered Design, Cognitive Task Analysis, Airborne Laser, Cognitive Requirements, Decision Making, SBIR Report	77
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNL

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. Z39-18

This page left blank intentionally.

SUMMARY

As information technologies are becoming more central to weapons systems, the burden is shifting from conventional human factors requirements, to cognitive requirements. This report explores the feasibility of different methodologies for capturing and understanding the cognitive requirements in envisioned worlds. The goal of the project was to identify methodologies that could be leveraged in a tool to help Program Managers and Directors of Engineering incorporate cognitive requirements early in the design cycle. Three methodologies are tested: *Cognitive Task Analysis (CTA)*, *scenarios*, and *Team Integrated Design Environment (TIDE)*. *CTA* involves knowledge elicitation interviews and analysis to understand the cognitive and decision-making aspects of tasks. *Scenarios* are a form of knowledge representation in which the cognitive requirements are described in the context of a mission. *TIDE* is a tool for determining optimal team configurations.

These three methodologies were tested in the context of Airborne Laser (ABL) Battle Management Command, Control, Communications, Computers, and Intelligence (BMC4I). The Airborne Laser is a program under development in which the crew is under pressure to make rapid decisions about whether or not to fire a chemical laser at enemy missiles. Information about cognitive requirements was collected via observation and CTA interviews. Various formats (including a scenario) were used to illustrate these cognitive requirements, and optimal team configurations were explored via TIDE. Some of the major findings from the project are described below:

CTA was useful in flagging the cognitively challenging aspects of the ABL mission and organizing the tasks involved into ten high-level functions. These cognitive challenges could be used to specify human computer interaction recommendations.

Team dynamics and potential breaking points were illustrated with a scenario of a potential ABL mission. TIDE was able to more evenly distribute workload across the crew and demonstrate the impact of reducing crew size.

Interviews with perspective users indicated that input about crew decision making would be valuable in developing the concept of operation as well as design, function allocation, staffing, and training.

These findings were used to develop initial ideas for a tool to conceptualize the dynamics and tradeoffs involved in cognitive tasks. Scenarios form the basis for this tool, called *Cognitive Requirements for Individuals and Teams: Evaluations, Recommendations, Inspection, and Analysis* or CRITERIA. The intent is that CRITERIA would capture cognitive criteria for tasks in complex systems and illustrate the implications through the use of simulation.

PREFACE

This effort was conducted under contract number F41624-99-C-6029 for the Crew Systems Development Branch, Crew System Interface Division, Human Effectiveness Directorate of the Air Force Research Laboratory (AFRL/HECI), Wright-Patterson Air Force Base, Ohio 45433-7022, for the period April 1999 to January 2000. Klein Associates Inc., 1750 Commerce Center Blvd. North, Fairborn, OH 45324 was the contractor. Aptima, 600 W. Cummings Park, Suite 3050, Woburn, MA 01801 participated as a subcontractor to Klein Associates Inc. Dr. Edward Martin (AFRL/HECI) was the Air Force Project Manager. This effort supported Work Unit 3005HC9F.

In addition to Edward Martin, we are grateful to AFRL/HECI's David Hoagland and Thomas Carretta for their support and feedback throughout the project. We would also like to thank LCOL Bob Devaney, the Airborne Laser (ABL) System Program Office BMC4I Integrated Product Team (IPT) Lead, for granting us access to ABL subject matter experts and Jim McCormick for helping us come up to speed on the ABL program. We are especially grateful to Jane Kline, the BMC4I IPT Human Factors Engineer from the Crew Systems Branch, Flight Systems Engineering Division, Engineering Directorate of the Air Force Aeronautical Systems Center (ASC/ENFC). It was she who led us to the ABL program, and helped us make contacts within the program.

We would also like to express our gratitude to colleagues at Klein Associates. Tom Miller and Rob Hutton presented constructive advice for strengthening the document. Barb Law and Tracy Fulk provided valuable assistance in the production of the document. In addition, Daniel Serfaty of Aptima offered input on the direction of the project.

This page left blank intentionally.

TABLE OF CONTENTS

This page left blank intentionally.

LIST OF FIGURES

LIST OF TABLES

This page left blank intentionally.

INTRODUCTION

This Phase I Small Business Innovative Research (SBIR) report addresses the technology that would provide a means for Program Managers to incorporate cognitive requirements into the design of new systems. As information technologies become more central to weapons systems, the burden is shifting from conventional human factors requirements to the cognitive requirements of operating systems designed around data flow and information management. System designers need tools that enable them to anticipate the cognitive demands placed on the operators of these systems. Moreover, cognitive requirements needs to be addressed early in the concept development stage of design, while a full range of options is still available. If the cognitive engineering is delayed until late in the design cycle, the degrees of freedom for improving the system will usually be too few. As constraints add up and the design moves towards closure -- it becomes increasingly costly to make changes to accommodate the needs of operators and users.

The discipline of cognitive engineering was developed in part to represent human requirements in order to improve design. Unfortunately, cognitive engineering has not yet had the impact that is needed. The key goal in this Phase I effort was to make the transition from cognitive engineering strategies applied in research and development efforts to more general and practical strategies that would provide information useful for Program Managers and designers.

Barriers to Cognitive Engineering Application in New Programs

Barriers to Achieving Program Emphasis for Cognitive Engineering

Currently, cognitive engineering methods are not applied until systems have achieved a reasonable state of maturity -- when it is already too late to significantly influence the design. The types of data relevant to cognitive engineering that Program Managers need are difficult to collect early in the system design process. Further, a Program Manager is typically facing a variety of hard, near-term challenges that demand his or her attention. For example, the system may require hardware or software breakthroughs that must be achieved in order to keep the project viable -- lack of these breakthroughs would then render cognitive engineering results moot in any event. In the case of the Airborne Laser (ABL) program, the challenge is to design a laser that is sufficiently small and light to be carried on a Boeing 747-400F, yet sufficiently powerful to function as a weapon. Meanwhile, the ABL Program Manager has to also resolve safety concerns, such as the stability of laser operations, the ability to deconflict the use of the laser so as to prevent fratricide, and the ability to handle hazardous materials involved in laser operations. Collateral issues such as the size and weight of fire suppressants also emerge periodically to demand the attention of

the Program Manager. The technical and logistical challenges faced by the Program Manager are considerable. In such a context, concerns about cognitive requirements take on less immediate importance. When all this is coupled with often-present uncontrolled variables -- such as the ABL's situation wherein the analogue system's (the Airborne Warning and Control System or AWACS) crew task loading is not as demanding -- it becomes very difficult to gain sufficient attention or emphasis on cognitive requirements.

Barriers to Applying Cognitive Engineering to Team Sizing and Allocation of Function

Cognitive engineering methods have primarily been applied to individual workstations. However when a Program Manager needs to be concerned with team functions at an early stage of design, the team composition and the requirements for team coordination are of equal or greater concern than are the requirements of individual operators. Cognitive engineering studies need to extend the current research to address team coordination, rather than continuing to emphasize design for individuals. The current methods for improving human-computer interfaces focus on aiding the individual operator. Methods for Cognitive Task Analysis (CTA) almost exclusively support individuals. It is often assumed that a team is a collection of individuals, and if we improve the performance of all the individual members, then the team performance should also benefit. However, this bottom-up approach ignores the emergent properties of teams (e.g., communication needs, information management, coordination issues, requirements for shared situation awareness), and its underlying assumption is not always valid.

Barriers to recommending team size. The field of human factors has fewer methods for recommending team size than it has for specifying individual cognitive requirements. A bottom-up strategy is unlikely to address the emergent properties of teams. For example, Klinger and Klein (1999) have described a program where staffing of the emergency response organization of a nuclear power plant was excessive, and performance gains were achieved by dramatically cutting the staffing. Workload actually went down as fewer staff members were incorporated in the team. If we are to support teams, we need to capture these emergent processes. We need to specify the requirement for shared situation awareness. We need to determine how skilled teams are able to maintain self-awareness. We need to develop methods for helping teams establish useful mental models of the roles and functions of each of the members. We need to identify the ways that teams pool their understanding to detect problems and make inferences.

Barriers to recommending team member requirements. Designing for teams is difficult because we do not have good methods for representing team performance requirements. Existing methods for describing teamwork often translate into massive wiring diagrams of interactions between each of the team members. This is another example of a bottom-up approach. The assumption is that by specifying all the

interactions, the insights must be someplace inside the proliferation of connection lines. In actuality, these types of comprehensive diagrams are not very intuitive, and are not very useful for guiding the design process. The complexity of team interaction is conveyed, but without the meaning of those interactions.

Decision-Centered Design Approach to Supporting Team-Design Decisions

This Phase I effort explored an innovative strategy — a Decision-Centered Design (DCD) approach to develop a tool to address the cognitive requirements of teams in a new, envisioned system. A decision-centered design approach relies on extensive front-end analysis to understand the problem. It also means working iteratively with potential users to obtain their feedback and ensure that their needs are being met. The DCD process is illustrated in Figure 1. Cognitive Task Analysis interviews are conducted with decision makers in order to understand their decision requirements or cognitive demands. These decision requirements are then used to recommend changes to design, staffing, or training. This process is repeated at several points in the project to ensure the decision makers' needs are being met.

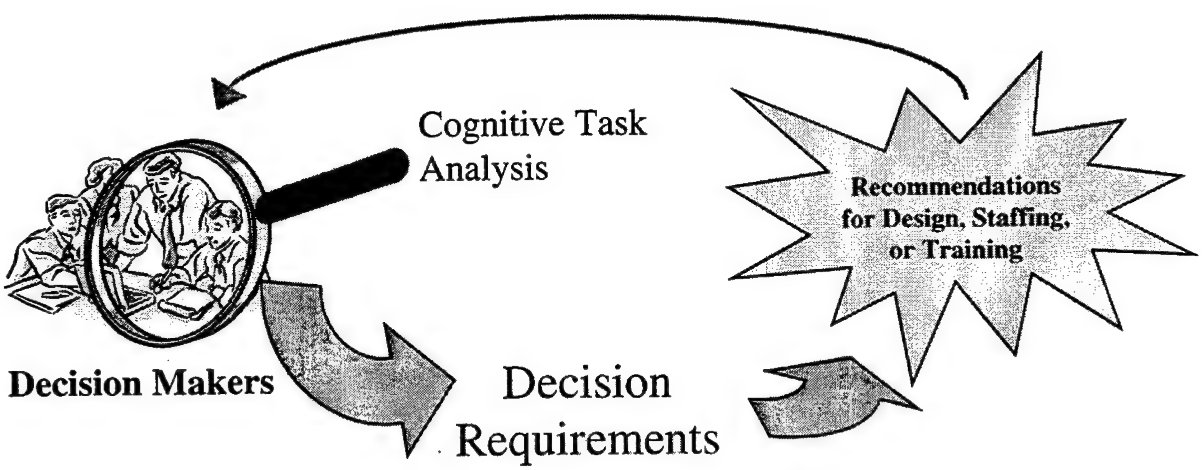

Figure 1. A decision-centered design (DCD) approach.

Too often, decision support systems are not designed around the decision-making aspects of the task. As a result, the systems fail to provide the necessary information, fail to provide it in a useful form, or -- as is often the case -- make it more difficult to access essential information. In the field of human factors this is known as clumsy automation (Woods, Johanessen, Cook, & Sarter, 1994), because the good intentions of the designers result in worse performance rather than improved performance. The decision-centered design approach, on the other hand, begins with a CTA study to identify the decision requirements of the task, i.e., the key judgments and decisions, the reasons why they are difficult, the types of errors that are

found, and the patterns and strategies used by experienced personnel. What is striking about this approach is that it does not begin with decompositions into basic procedure-oriented, perceptual-motor tasks or determinations of information flow. Instead, it fits within user-centered design approaches (e.g., Landauer, 1995) by focusing on the decision requirements for performing the task well, and uses these to design the architecture of an information-management system.

Klein Associates has successfully applied aspects of DCD in previous design projects (Klinger & Gomes, 1993; Miller & Lim, 1993) with high degrees of success. Klinger, Andriole, Militello, Adelman, Klein, and Gomes (1993) report a careful evaluation that determined that performance of an AWACS Weapons Director was significantly improved by an interface design based on decision requirements. Miller and Lim (1993) designed a decision support system for Air Force weaponeers. It was enthusiastically received by the operational users, and its sponsors moved rapidly to system development.

However, we have also been learning that having feasible and useful methods is not a guarantee that they will be adopted. We have learned that it is essential to influence design from the beginning, when the statement of need is issued by the design requirements analysts, and the program office conceptualizes a strategy for satisfying the need. As the system is taking shape -- as the weapons system is being defined -- it is critical to articulate the cognitive requirements of the individuals and the crew who will be operating and supporting it.

In this project, we have begun to develop a decision-centered design methodology for use during the conceptual design of systems, so that the program designers have a tool for considering cognitive requirements. Such a tool will enable them to generate more effective designs, to identify important questions that could trigger research activities early on, to set cognitive criteria for the contractors who will be engaged in the detailed system design, and to specify acceptance criteria to be used during test and evaluation.

The use of a DCD tool would allow the using command to look downstream and safeguard the operators who will eventually inherit the system. It is too easy for the operators' needs to be overlooked during system development because the focus and milestones are typically on hardware and software delivery, and the compromises that reduce usability are often invisible to the operational community. By placing cognitive requirements in the mix of design criteria from the beginning, we hope to afford protection to the operators by making their needs a viable part of the design process from the beginning. Failure to do so will lead to systems that create barriers to the operators' understanding of situations, and lead to human error.

Overview of the Phase I SBIR Approach

The overall goal of this project was to help Program Managers address cognitive requirements of teams early in the design cycle. In order to develop a software tool to accomplish this we conducted two major series of tasks. One series of tasks involved testing the feasibility of different methods to determine how well they would support a Program Manager. These methods included: *Cognitive Task Analysis*, *Team Integrated Design Environment (TIDE)* software, and *scenarios*. The domain of ABL was used as a testbed for these methods and tools. Rather than attempt a highly-detailed study (which would take far too long, require far too much data, and would require types of data that would not be available until late in the design cycle), Klein Associates explored what could be accomplished with initial data as a framework for exploring the design tradeoffs involving the crew members. The results of each method and feasibility for use in a Phase II software tool are discussed in the *Results of Phase I* section of this report.

Two series of tasks (illustrated in Figure 2) were conducted in parallel in order to accomplish our overall goal to develop system concepts for a tool to support Program Managers. CTA interviews were conducted with Program Managers in order to understand the challenges of program management and how we could support those challenges.

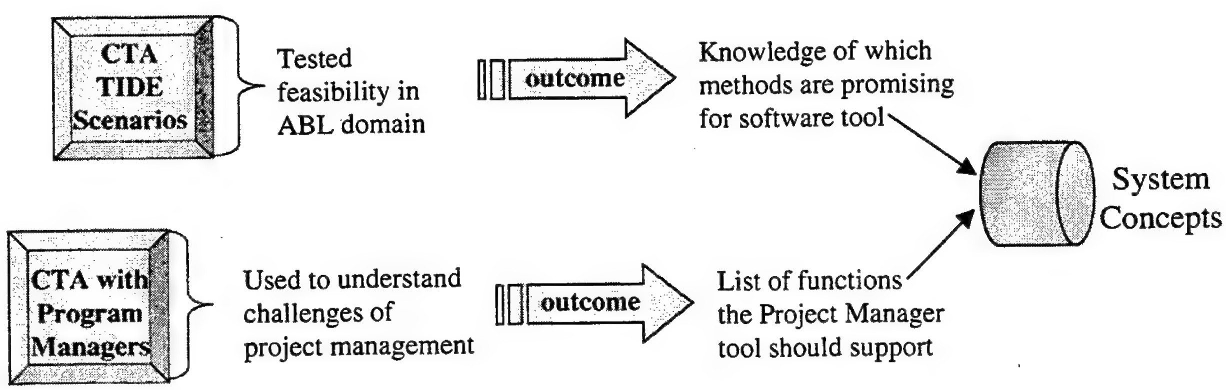

Figure 2. Two major tasks in Phase I.

There were several innovations to this project. Program Managers and directors of engineering were targeted as the user, rather than design engineers who are responsible for system development. This is a critical shift. While the findings from a preliminary DCD would be relevant to design engineers, we believe that the greatest impact can be realized by incorporating cognitive requirements into the initial design concepts. The second innovation was to use a DCD approach to focus on decisions rather than procedures. The third innovation was to focus on the team rather than individuals.

The advantage of the DCD approach is that it offers Program Managers and design-requirements analysts a means for taking cognitive requirements into account early in the design cycle, and for anticipating the consequences of decisions such as crew size, qualifications level, configuration, and training requirements.

Rather than trying to provide recommendations, we have concluded from the Phase I effort that it is more feasible and useful to present the findings in the form of decision scenarios. Program Managers can use these scenarios to understand the dynamics of how the crew will have to make key judgments and decisions and will have to coordinate during critical events. Instead of trying to represent workload as an amorphous concept, we are trying to capture the specific types of coordination patterns that may be found during high workload periods. Following the work of Schwartz (1991), we are using decision scenarios as a means for learning about tradeoffs, instead of attempting a premature set of recommendations.

METHODS

Three methods seemed promising in their ability to capture and represent cognitive requirements of teams. During Phase I, we tested each of these methods in the domain of ABL to determine which methods, or aspects of the methods, were most promising for inclusion in the Program Manager tool. One requirement for selection is that the methods work in the early stages of system development when less information about the system and the users is available. The three methods tested were:

- Cognitive Task Analysis (CTA) for capturing and representing aspects of teams and cognition in an envisioned world.

- TIDE for providing insight into the optimal configuration of teams and the assignment of roles and functions.

- Scenarios as a tool for representing the critical decisions and aspects of team coordination in context.

In addition, we conducted CTA interviews with Program Managers to understand their challenges and how they could best be supported.

Airborne Laser Background

The domain of ABL was chosen to test feasibility of methods for several reasons. The program is relatively early in the development cycle and therefore could benefit from insight into the cognitive

elements of the task. The ABL program was also dealing with issues related to staffing -- the allocation of roles and functions among crew members and the identification of appropriate Air Force specialty codes (AFSCs) to fill each position. These issues made ABL a good candidate to test feasibility of CTA and TIDE for envisioned worlds.

ABL is a weapon system designed to shoot down theater ballistic missiles during the boost phase in the first line of defense. Once a missile launch is detected, two illumination lasers are used to acquire the target and provide information regarding air turbulence. The beam control system computes information about target acquisition and compensates for atmospheric distortion. A high energy chemical laser then strikes the missile so early that the missile and its warhead do not leave the country that launched it. All this is accomplished from a modified Boeing 747 flying behind the engagement zone. One of the interesting aspects of ABL is that -- because of the speed of the events involved -- the laser will normally shoot down the missile automatically. It is the crew's job to determine whether or not to stop the shot. This is true command by negation.

In researching the ABL, it is easy to find information about the physical systems on board -- the different lasers that will be used and the physics involved. News stories are full of details about the systems but often fail to mention the crew who will be operating, monitoring, and keeping those systems functional. As we began to get involved in the ABL program, we heard more concerns about the crew members and efforts to understand crew requirements. In fact, it was crew composition and crew dynamics that was one of the unknown factors. Our goal in the Phase I ABL analysis was to understand the critical decisions the crew will face as a whole, how difficult those decisions were, and why they were difficult. Understanding this information will benefit the design, staffing, and training in the ABL program.

Cognitive Task Analysis of Airborne Laser

CTA provides a set of tools for eliciting general domain knowledge and specific knowledge pertaining to the decision requirements for the critical decisions. CTA comprises both knowledge elicitation (interviews and observations with subject matter experts) and knowledge representation (analysis and meaningful representation of the data).

The CTA of ABL allowed us to go beyond the procedural textbook knowledge and the behavioral aspects of a task that are traditionally elicited and represented by a behavioral task analysis. The tools we used allowed us to understand some of the cognitive aspects of the ABL mission -- in particular the judgment, decision-making, and problem-solving skills that are so critical in the time-pressured, uncertain, and ever-changing air combat environment.

In this effort, a full CTA was not feasible for several reasons. This is an envisioned problem so ABL experts do not exist and we had to adjust our methods accordingly. We did talk to subject matter experts of analogue systems such as AWACS. Often in new systems there is a shortage of time to interview and study experts. Therefore, we conducted an abbreviated CTA in which we tried to identify the cognitively challenging tasks and decisions for the individuals and the crew.

In preparation for the CTA, we met with an ABL subject matter expert for half a day to learn about program status, current design approach and constraints, technical aspects of ABL, and what they would want out of our cognitive engineering projects. The second knowledge elicitation was conducted at Kirtland Air Force Base during the Joint Expeditionary Force Exercise 1999 (JEFX-99). We were able to observe a subset of the Battle Management Crew as they participated in the simulation. We were able to observe how the crew reacted to routine tasks such as monitoring the situation and refueling, as well as their reaction to non-routine events such as missile launches and enemy attacks. We were able to discern information about critical decisions and judgments of different crew members and the crew as a whole. Other observations focused on coordination issues, information needs, and interactions with the displays.

In addition to observations, we conducted informal interviews with the crew members. We were able to ask questions during down-times — both during the simulations and at the end of the day. Our questions were aimed at understanding the difficult decisions, judgments, and coordination issues. Sample questions included:

- What is difficult about the ABL mission, and what is difficult about each particular job position?
- What aspects of your training prepared you for this assignment?
- What are the challenging decisions that you would not trust to someone with less experience?
- What experience or knowledge is needed to make those decisions?
- What information do you need to make that decision?
- What are the difficult teamwork issues?
- What are you seeing and hearing, and how is that affecting your actions?
- At different points in the mission -- who do you want sitting next to you and why?

To facilitate analysis, detailed notes of the interviews and observations were generated. We then had to determine how to make sense of the large amount of context-rich data collected. We chose to identify the cognitively challenging tasks and information about why the tasks are challenging. In tailoring CTA methods to envisioned worlds, it is important to identify potential cognitive demands early so they can be supported by the design, staffing, or training. This is the type of information we identified during Phase I.

In order to accomplish this, Klein Associates generated a list of the tasks, decisions, and functions involved in the ABL mission. We limited our analysis to the "engagement" phase of the mission – the events between takeoff and landing, excluding pre-mission planning and post-mission debrief. The tasks, decisions, and functions were at a mid-level of granularity. They were at a higher level than tasks such as button-pushing and at a more detailed level than "maintain situation awareness." Examples of this mid level include "determine best orbit placement," and "monitor enemy air tracks."

The tasks, functions, and decisions were then sorted into ten major categories or functions. The items were sorted according to what overall function the task played in the ABL mission. For example, "monitor enemy tracks" could be part of *maintain plan flow* as well as *self-protection*. For each task, we used our knowledge of the domain and information from interviews and observations to determine how cognitively challenging the task was, why the task was cognitively challenging, and other cognitive information associated with the task. We applied ratings of *high*, *medium*, and *low* to reflect how cognitively challenging we judged a task to be. *Low* indicated that the task was not very cognitively challenging and that little or no additional CTA data were needed on the subject. *Medium* indicated that there was a fair amount of cognitive complexity involved and the topic would benefit from additional CTA probing. A rating of *high* indicated a large degree of cognitive complexity and expertise was involved and that additional CTA would be beneficial to further understand the cognitive nature of these tasks. For each task listed in Table 1 and the ten tables in Appendix A (under the column entitled "Decision/function"), a description of what we found that made the task cognitively challenging is included (under the column entitled "Why challenging").

The heart of the ABL analysis was the development of a scenario to bring to life the critical decisions, judgments, and coordination involved in the ABL mission. In developing the scenario, a list of several key events and accompanying decisions was developed. These events were then organized sequentially in a timeline and the details were fleshed out in the story. The scenario was then annotated to highlight the cognitive and team aspects of the tasks.

In addition to the above analyses, we made several sweeps through the data to pull out the major findings. These were findings that could have a major impact on design, staffing, or the development of training requirements.

TIDE Analysis

Analysis was also conducted using Team Integrated Design Environment (TIDE) to analyze workload and determine the optimal team configuration. The TIDE organizational design methodology was mission-driven. That is, the model used information about the tasks required to accomplish a mission and the resources available to accomplish those tasks, and used algorithms to optimally allocate these tasks and resources to team members to create an organizational structure. To capture the tactical and operational elements in a scenario, the research team relied on input from the CTA.

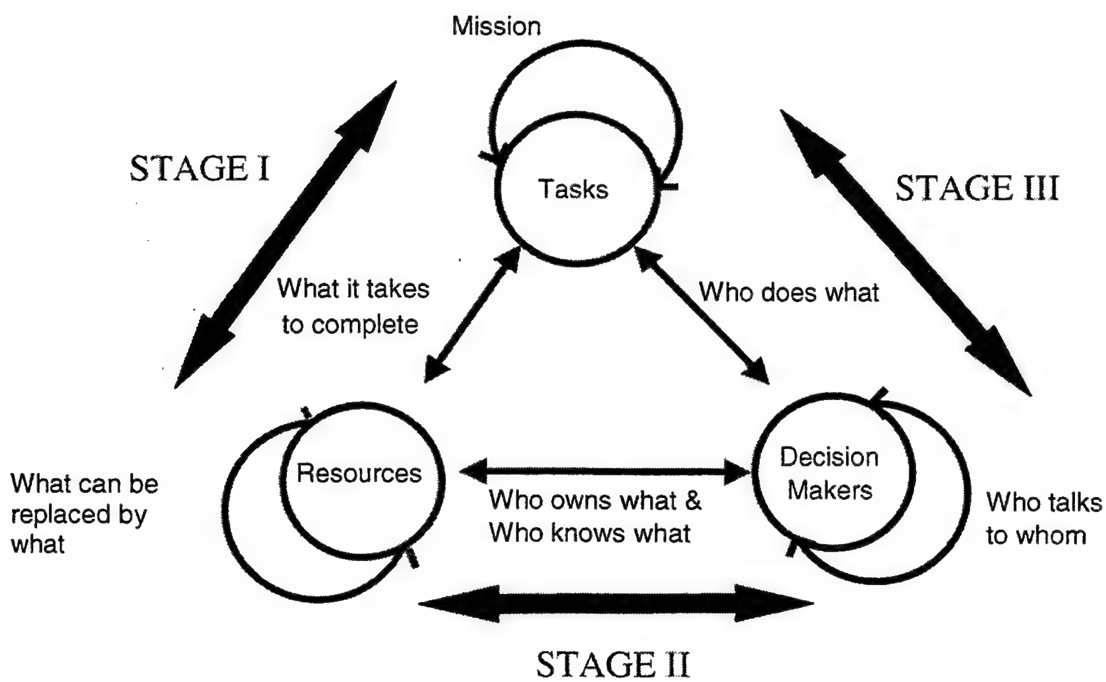

Figure 3. TIDE three-part allocation model.

The TIDE approach was based on a *three-part allocation model*, presented in Figure 3, that considers: 1) mission tasks, 2) system resources, and 3) human decision makers (the ABL crew). The organizational design process is, in simplest terms, an algorithm-based allocation between these three parts. In TIDE, organizational performance is assumed to be a function of a variety of design parameters -- including individual workload, distribution of responsibility, communication between decision makers, coordination of resources, information processing efficiency, and information transfer efficiency. To

apply the TIDE methodology, we needed to know the sequence in which tasks were performed, the resources that were used to perform each task, and the interdependencies among tasks. Given this information for a specific mission scenario, our modeling techniques suggested ways that tasks should be grouped together (i.e., handled by the same person or the same group of people) in that scenario in order to both satisfy organizational constraints and optimize performance according to different possible criteria (e.g., equalizing workload across people).

Task Decomposition.

Using the CTA data, the ABL mission was divided into three overall mission phases or functions: Monitoring, Self Defense, and Missile Elimination. Within each of these functions, a series of mission tasks was specified. For example, "monitor screen and alerts for missile launch" is a task within the monitoring function. Each of these tasks was classified into Action, Decision, Information, and Outcome categories. Using these components a task diagram was developed for each mission phase to understand the functional and temporal relationships between the tasks. An example of a task dependency diagram is presented in Figure 4.

In addition to defining the inter-task relationship, the relative time to complete each task (in minutes) and the relative workload (on a scale of 1-5) of each task were estimated. Workload for each action and outcome task was an estimate of the relative effort. For the decision tasks, workload was an estimate of cognitive effort. For the information tasks, workload was defined as processing effort.

Interviews with Program Managers

Since our eventual goal under Phase I was to build a support tool for Program Managers, we conducted interviews to understand our users' needs. We interviewed a total of four Program Managers from both the military and the commercial sector. Each interview lasted approximately one hour. These were high-level Program Managers in charge of the development of new systems. The purpose of the interviews was to understand the challenging aspects of the Program Manager's job, especially as it relates to incorporating cognitive requirements into the system design requirements. In addition to understanding challenges, we collected information about their information needs: which tools and methodologies worked and which didn't, what type of information was useful at different stages of development, and what information they wished they had known sooner. Understanding the challenges, decisions, and information needs of Program Managers will better enable us to support them.

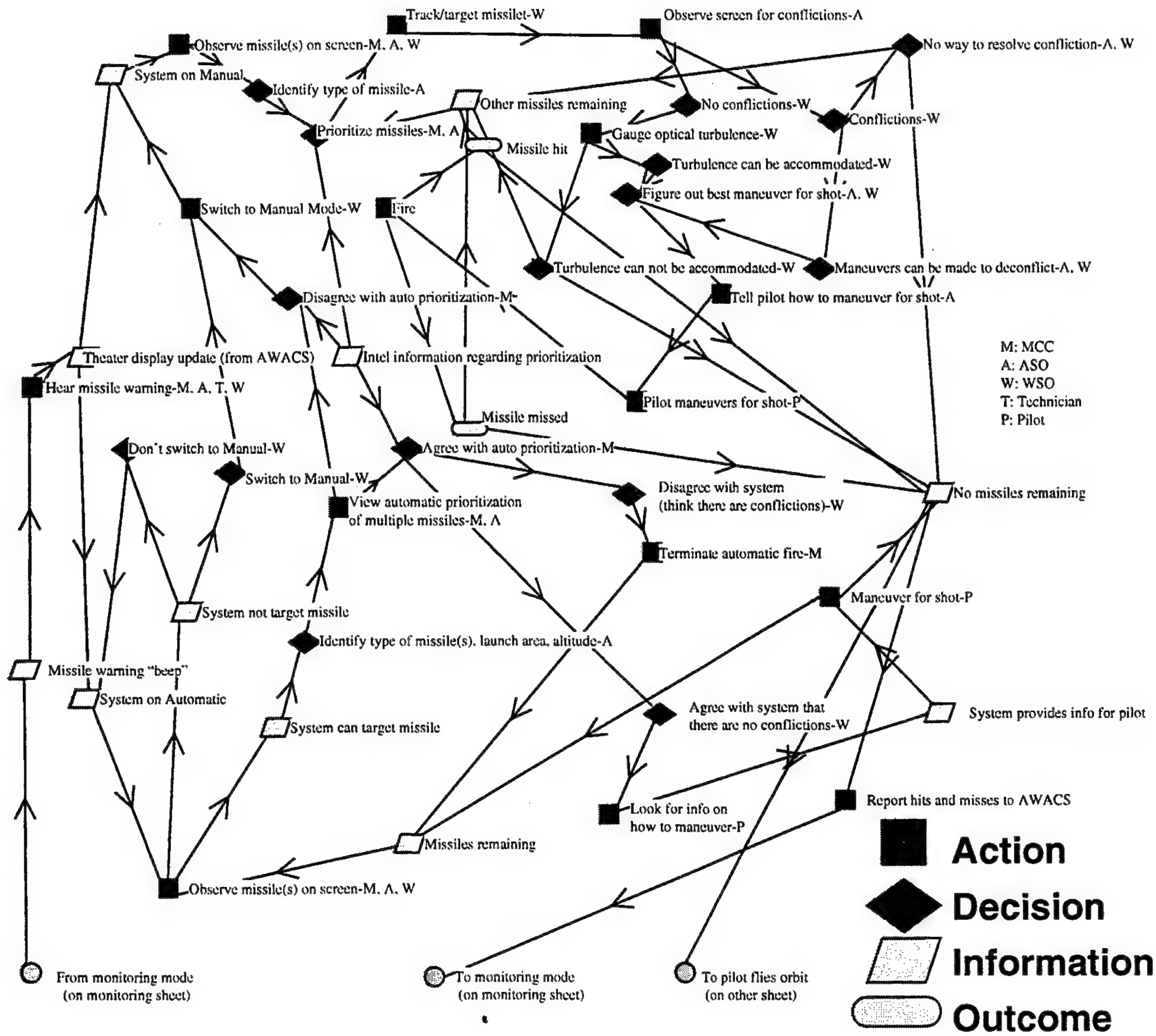

Figure 4. Task dependency diagram.

RESULTS OF PHASE I

Overview

Included in our key findings was that we could identify individual and team requirements, and that there were surprises between the tough decisions we identified and the ones we were briefed about. For example, we were told that one of the toughest decisions the crew would have to make was determining whether to take the shot in a short window of time. We observed that the system decides whether to take

the shot, and the human monitors the situation and may decide to prevent the shot. We were then told that the tough decision was deconfliction -- determining whether any aircraft were in the path of the laser. However in observing the simulation and talking with operators, this did not appear to be very cognitively challenging. This is because the system automatically deconflicts in automatic mode. In most cases when the system is in automatic, the operator will not have to worry about deconfliction (as we observed in the simulation). The only time the operator will have to perform deconfliction is in manual mode. The challenges in this case are that the operator needs to think three-dimensionally to determine if there is anything in the path of the laser and that s/he needs to do this under extreme time pressure.

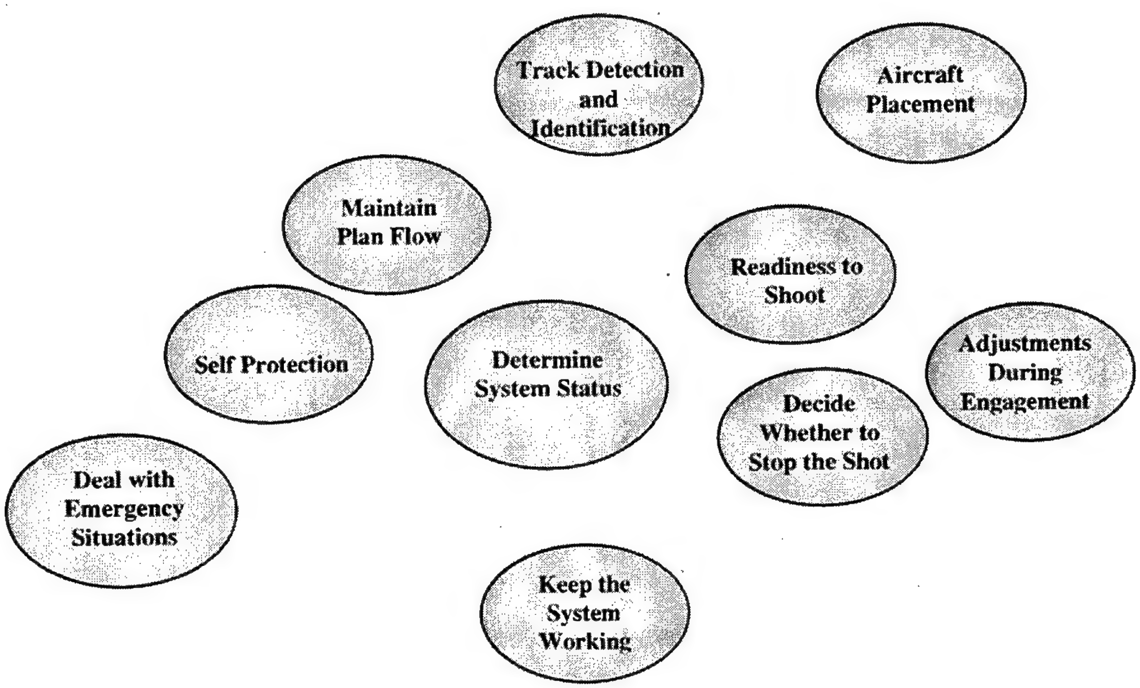

Figure 5. High-level airborne laser functions.

The major tasks and decisions were organized into ten high-level functions (see Figure 5). These are functions that the crew as a whole needs to accomplish. They are not broken out by position. This is because, ideally, in an envisioned world this analysis would be done before the number or roles of personnel have been decided. Proximity to other functions indicates how related one function is to the other functions. These are not discrete categories; there is overlap of tasks and decisions among the categories. Each of the functions is briefly described below.

Self Protection. There is considerable overlap between this function and *Maintain Plan Flow*. Both functions involve monitoring enemy tracks, Combat Air Patrol (CAP) location, and status of sensors and communications. Self Protection also involves critical functions of gauging threat to ABL and

determining when and where to retrograde. Gauging threat to ABL requires identification of the type of threat. Often, it is the missile the aircraft can carry, rather than the type of aircraft that is the determining factor. The crew must think ahead and anticipate enemy actions.

Maintain Plan Flow. This function encompasses everything the crew does to obtain and interpret information. Some of the critical tasks are: detecting problems and inconsistencies, monitoring track number changes, applying commander's intent, and orchestrating priorities. One of the challenges that comes up again and again in this category is resource allocation. Resource allocation is relevant because there is a limit to how much information a person can process at a time, there are a limited number of people to accomplish a variety of tasks, and many of the tasks are critical and need to be accomplished immediately.

- *Aircraft Placement.* Aircraft placement affects the ABL's readiness to shoot. Launch sites and times must be anticipated in advance so the ABL is in a position to shoot. This involves discerning trends of missile launches. There are several aspects of aircraft placement that must be considered; these include: placement of the orbit so the ABL covers known launch sites but is not at risk, type of orbit (circle, figure eight, etc.) so the launch sites are covered the maximum amount of time, and placement within the orbit. During the exercise, we heard the Mission Crew Commander (MCC) ask several times how long it would be until the aircraft made the turn [and would be pointing in the right direction to shoot down enemy missiles]. This function is made more difficult because it will require team coordination between the several members of the battle management crew and the flight crew (the crews are not co-located).

- *Determine System Status.* This function is located near the center of the diagram to illustrate its relevance to many of the other functions. In order to accomplish many of the other functions, such as Maintain Plan Flow and Determine Readiness to Shoot, the crew needs to know whether the systems are functioning correctly and whether they can trust the data on their displays. The crew must be adept at noticing when something is wrong with the systems. This is not a trivial task, as it often involves "seeing what is not there" -- in other words, what data were expected and what data are missing?

- *Track Detection and Identification.* This function is important and is applicable to Maintaining Plan Flow, Self Defense, and Determining Whether to Stop the Shot. Operators must locate tracks by number, use standardized voice tell formats, and accept or reject automatic

identification recommendations. Accepting or rejecting recommendations requires an experience base to detect errors and detect subtle cues about the tracks.

- *Readiness to Shoot.* Readiness to shoot refers to whether the ABL is capable of shooting a missile at any given time. This is something that must be continually assessed to ensure that the amount of time during which the ABL is capable of taking a shot is maximized. Some factors involved are: whether the aircraft is turned the correct way, the weapon status (whether the laser is ready to shoot), and the status of the link.

- *Decide Whether to Stop the Shot.* This may be a straightforward decision if the system is in automatic mode. In the automatic mode, the system performs deconfliction with aircraft and prioritization among missiles. The main difficulty in automatic mode would be deciding to reprioritize based on new information that has not yet been entered into the system's prioritization scheme. Deciding whether to stop the shot when the system is in manual mode is much more cognitively challenging because the human must perform deconfliction and prioritization. Deconfliction in manual mode involves forming a three-dimensional picture of the world to see if there is anything in the projected path of the laser. In order to perform prioritization in manual mode, the operator must have an understanding of the prioritization scheme and be able to apply it. Another difficulty in deciding whether to stop the shot has to do with resource allocation -- in terms of how many shots the laser has left. This is not a preset number, it must be estimated based on range from the missile, when the missile can be engaged, and how long the missile must be engaged. The operator may decide to stop the laser from firing at a lower priority target in anticipation of a higher priority target.

- *Adjustments During Engagement.* This involves all the tasks and decisions that may need to be performed once the decision has been made to allow the shot. Some examples are: acquire target (in manual mode), determine if the missile is at a good altitude to shoot, determine why the system will not engage (in automatic mode), perform deconfliction, and determine how long before the missile can be engaged. Estimating the time until missile engagement is dependent on the angle of the missile, the altitude of the missile, and the ABL's placement in its orbit. This information is important because it will help the decision maker determine if there is enough time to engage the missile or if the shot will be lost. None of the tasks are trivial on their own. Deconfliction involves special discrimination, and there is only a short window of time to take the shot. These tasks are made even more challenging by the fact that they all must be accomplished in a short period of time.

- *Deal with Emergency Situations.* These are functions that would not normally occur during an ABL mission that went as planned. However, these are events and decisions that the crew must be ready to handle. Some examples are: deal with chemical leak, determine whether to perform an emergency landing, and recognize jamming. In many of these functions, the danger to the crew must be gauged and the implications of actions must be understood.

- *Keep the System Working.* These are all the tasks involved in the upkeep of the different systems onboard the ABL. Many of the tasks are routine and procedural, such as initialize computers and switch configurations between users. Other tasks and decisions are more difficult, including prioritizing which system to fix first if multiple systems simultaneously fail and determining how to work with degraded systems.

Another major finding had to do with crew composition. One of the assumptions is that AWACS is a good analogue to ABL. However, there are significant differences between the MCC roles on AWACS and Airborne Laser. Airborne Laser is a single mission platform while AWACS can have multiple, simultaneous missions. One implication of this is that the AWACS MCC may be overqualified for the job.

Cognitively Challenging Aspects of Airborne Laser Missions

This section describes the cognitive challenges of the ABL mission. Each of the high-level functions in Figure 5 contained many subtasks and decisions. The sheer number of subtasks and decisions in each function make most of the high-level functions appear cognitively challenging. Therefore, in order to decipher which major aspects of the ABL mission were cognitively challenging, we examined the individual tasks and decisions. For each task, we rated how cognitively challenging it was (low, medium, high), described why it was cognitively challenging, and provided additional CTA data or questions to be answered. A sample of the type of information presented is extracted from Table A-2 and presented in Table 1. The complete set of tables for each of the ten major functions can be found in Appendix A.

The CTA approach was valuable in identifying the cognitive elements involved in the ABL mission as well as team coordination aspects. The CTA was useful in determining which aspects of the task are cognitively challenging and why they are challenging. We believe this information would be useful because it identifies the high drivers or leverage points in terms of cognitive and team elements. This information could then be used in determining function allocation and staffing requirements. We also believe that this type of information would be available early in the design process (although at a lower

level of resolution or fidelity). All these factors suggest that CTA will be a valuable tool in eliciting team cognitive requirements in an envisioned world.

Table 1. Some Cognitive Challenges involved in the ABL Mission

Decision/function	CC*	Why challenging	Additional CTA data
2.1 Monitor enemy tracks	Med.	There are multiple tracks that can disappear and reappear. The enemy will often be trying to use deception so operators need to maintain enemy perspective to make sense of what they see on the screen. Tracks can carry weapons that can be a threat from farther away than the original track itself. Need to project ahead and understand implications of enemy actions.	
2.2 Filter and sort information	High	Need to make meaning and draw conclusions from the information (synthesize). If information is ambiguous, missing, or incorrect, it can make filtering and sorting difficult. If too much information is coming in, it can be difficult to identify which information is relevant.	Operators need to filter the information that is displayed. All data blocks are not the same; it depends on the track. For example, altitude is not necessary for ground and surface tracks. Modes and codes are not necessary for all tracks.
2.3 Determine whether sensors and communications are working	High	Must notice inconsistency in data. In other words, you need to see what is not there. Indicators may not reflect exactly what the system is actually doing. It is easy to assume that information is being sent and received if there are no indicators to let you know something is <u>not</u> working.	

* CC stands for Cognitively Challenging

Table 1. Some Cognitive Challenges involved in the ABL Mission (continued)

Decision/function	CC	Why challenging	Additional CTA data
2.4 Determine where strikes are taking place	Low	Information is available in the Air Tasking Order (ATO) and on the screen.	A maneuvering surface to air missile (SAM) suggests a strike package is taking place.
2.5 Detect problems and inconsistencies in track data	High	This is dependent upon the number of sensors you have out there, the sensitivity of the sensors, and the location of the sensors. Inconsistencies may not stand out, or they may occur frequently enough that the important ones do not stand out more than the unimportant ones. Need experience base to compare situation and recognize anomalies.	Display aid – a tool could be built to track certain aspects during critical salient events. It is difficult to maintain situation awareness and not narrow your focus during a critical event. A display aid could show relevant information without distracting the operator from the focus.
2.6 Know and apply commander's intent	High	Involves applying commander's intent to the current situation and determining if your actions are consistent. This can be difficult if the commander's intent is poorly articulated or focused at the wrong level of granularity.	
2.7 Switch configuration between users	Low	Need to determine the level of information you need to know (big picture versus specifics).	This needs to be done quickly without re-logging in as a new user. If the display and its accompanying switch actions to do this task are complex and deeply embedded in menus, it can make the task much more difficult.
2.8 Perform spatial and audio discrimination between voice communications	Low	Need to determine who is speaking (source of information) at the same time you are listening for relevant information.	

Table 1. Some Cognitive Challenges involved in the ABL Mission (continued)

Decision/function	CC	Why challenging	Additional CTA data
2.9 Monitor location of high value assets (HVAs)	Med.	Can be difficult if, for security reasons, the locations of the HVAs are not widely disseminated. Some individuals on Airborne Laser may not have high enough clearance to be entitled to this information.	Display aid - have the HVA stand out by placing a circle around them or using a different color.
2.10 Monitor track number changes	Med.	Need to integrate information from multiple sources. One difficulty with track number changes is that operators often type in the track number of interest (once they 'learn' it) and a change in numbers can have them inadvertently looking at the wrong track. Operators may need to unlearn the old number as well as learn the new number.	Tracks may be picked up by multiple sensors, especially in joint operations (e.g., by a U.S. AWACS, a NATO AWACS, an E-2C, an AEGIS cruiser). Given the possibility for multiple sensors to acquire the track, there is a need for all of these linked data sources to be "correlated." There is a chance that tracks can be given multiple track numbers until the system correlates. As a result, there could be situations where a track number could be changed.

Scenario of an Airborne Laser Mission

This section demonstrates the use of a scenario in representing cognitive and team issues. The purpose is to explore the usefulness of a scenario in representing these issues, not to predict what actually might occur in an ABL mission. One of the major challenges in data analysis and representation is in capturing the dynamics and bringing to life the context in which a new system will operate. We believe that scenario tools fill this void and will enable Program Managers to better communicate their intent. The following story is an example of the scenario approach. The story is a fictitious demonstration of a portion of an Airborne Laser mission, told from the perspective of the battle management crew. The story illustrates a sampling of the cognitive and decision-making elements of an Airborne Laser mission. The story's narrative is on the left. Margin notes are included on the right to indicate the decisions, cues, factors, or difficulties in making decisions. The margin notes are the key to communicating the specific cognitive aspects to be supported.

SCENE: A troubled corner of the Middle East in the near future. The Airborne Laser entered the situation one week ago. Their mission is to shoot down enemy missiles before the missiles reach friendly territory. The battle management current crew consists of Major Doug Warren (Mission Crew Commander), Major Hal Krasneiwski (Air Surveillance Officer), Lieutenant Tom Collins (Weapons System Officer), and Sergeant Mike Ramsey (Technician).

ACTION	DECISION/COGNITIVE REQUIREMENTS
"Something's wrong," said Lieutenant Collins as he studied his computer screen. Collins focused on the displays in front of him. One provided a bird's eye perspective of the earth beneath him along with tracks indicating friendly and enemy assets. The other display was like a slice through the air picture in which he could see the altitude of all the aircraft in relation to the Airborne Laser. As Weapons System Officer, it was his job to make sense of the displays and stay aware of friendly and enemy aircraft locations.	**Decision:** Determine if the systems are working correctly **Cue:** Must see what is not there, know the system well enough to recognize when something abnormal occurs **Decision**: Maintain awareness of aircraft locations in order to quickly determine whether there is a conflict
Something doesn't seem right he thought. He peered at the two perspectives, integrating them into a 3-dimensional picture in his mind. *There, that's it – the tracks on the left hand of the display are not matching up*. Collins noticed that some of the tracks on the bird's eye view display were not showing up on the altitude display. He turned to the technician across the small space. "Hey, Sergeant Ramsey, take a look at these screens. The displays don't seem to be matching up."	**Decision**: Determine location of aircraft within 3-dimensional space **Cue:** Absence of tracks where there should be tracks (seeing what is not there)
What now? thought Ramsey. He was in the middle of running a diagnostic on the laser. What was supposed to be a routine task had turned out to be more problematic than expected. The diagnostic indicated an error with the pressure sensor in one of the chemical chambers. Ramsey walked over to the Weapons System Officer to see what the problem was. As soon as Collins pointed out the mismatch, Ramsey realized what must be wrong. There must be something wrong with the data link from AWACS.	**Decision:** Determine whether the sensors can be trusted **Decision:** Determine malfunction **Cues/factors:** Uses vast technical knowledge and understanding of the system affordances to recognize malfunction
Just then the Mission Crew Commander Major Warren came over to see what's wrong. Ramsey and Collins filled him in on the situation. "I need to know which information is good. Otherwise we are as good as blind in this area," stated Collins. Ramsey explained that there was also a problem with one of the laser sensors. Both problems required immediate attention.	**Information needs:** It is critical to know which information is accurate

Warren considered the situation. *Without those displays the Airborne Laser is at risk and we may not be able to destroy any missiles. But I need the laser sensors to make sure the whole place doesn't blow up.* Major Warren then realized an important piece of information - there were backup systems programmed to sound a warning if pressure or heat rose above certain levels. Warren ordered Ramsey to divert his attention to the display problem. "I'm giving you 5 minutes to see what you can do with the link. We'll have to rely on the backup sensors while you fix the link."	**Decision:** Prioritize to determine which system to fix first Perform mental simulation to understand implications **Cue/factor:** Backup warning sensor exit (needs mental model of the system to determine this) **Teamwork:** Establish priorities and deadlines
Ramsey returned to his computer console and halted the sensor diagnostics so he could use all resources on the link issue. Ramsey began to work and Warren looked at his watch. *If we can't bring up the link, we cannot continue our mission.* As Warren prepared to radio Airborne Command and Control and update them on their situation, Ramsey reported that he had isolated the problem and would have the system running in a matter of moments.	**Decision:** Mission go/no-go **Decision:** Whether to retrograde and where **Cue:** Status of the systems, are the laser functions affected? Will they be able to respond to a launch? Will the ABL be able to perform self protection?
That's better thought Collins as new tracks flashed on his screen. The displays were now consistent. The updated air picture was not surprising. Air superiority was demonstrated early in the week. Since then there had been only sporadic air activity by the enemy. The enemy activity that occurred was mostly harassment of friendlies near the border. That had been true today as well. In fact, the only activity in the last few hours was the systems going down.	**Cues/factors to maintaining SA:** Radar tracks, typical enemy actions and trends, general air picture Need to keep engaged in the task, even during inactive times
Thirty minutes later that picture changed. The Air Surveillance Officer, Major Krasneiwski (Kraz) was the first to notice anything. "Four MiGs rapidly approaching the border from the east. It looks like we might see some action," reported Kraz. The other crew members sat up straighter in their seats. They were all thinking the same thing. Enemy air attacks were often accompanied by missile launches. "How long till we reach the end of our orbit?" asked Warren. A quick look at the display showed that they were not in optimal position to defend against a launch. "Our current orbit won't bring us around into position for about 15 minutes or so," replied Kraz. *That's not soon enough* thought Warren. He requested the pilot to begin turning immediately to provide maximum engageability. *The launch is likely to come from two areas, based on what we've seen in the last few days. If we don't turn now, we won't be able to cover them both.*	Expectancies violated – enemy is not following their normal pattern **Decision:** Anticipate launches **Cue:** Enemy air attacks often precede launches **Decision:** Time to reach end of orbit **Judgment:** Is ABL in optimal position to engage missiles? **Decision:** When and where to turn – dependent on current speed and direction, anticipated targets

A familiar "BEEP" confirmed their expectations and a flutter of activity began. Collins looked at his screen to find the location of the launch. Fortunately, the Airborne Laser was aligned in the correct orientation to cover the missiles while completing the turn. A quick scan of the laser sensors showed that the system was ready to fire.	Notice launch and locate the missile track amidst other tracks **Decision:** Are potential missile sites covered? **Decision:** Is the system ready to fire? **Cues:** Amount of laser fuel, sensors indicating status of laser components
Collins remembered that one of the sensors was malfunctioning. "Ramsey, did you ever get that sensor fixed?" he asked the technician. "The laser is ready to fire," responded Ramsey. Meanwhile, the system (in automatic mode) locked onto a track and prepared to fire as soon as the missile came into range. Collins continued to monitor the situation and saw no reason to stop the shot.	**Decision:** Determine accuracy of sensors **Decision:** Whether to stop the laser from firing **Cues/factors:** Presence of higher-priority missiles, whether the laser is functioning correctly, conflict with aircraft (however, this is handled by the system when in automatic mode)
Suddenly the Weapons System Officer noticed another missile launch on the screen. "Another two missiles launched at the south site," he announced. Warren thinks *the south site is the Colonel's priority. I wonder if we have time to get them all.* "How long until we fire at the first missile?" Warren asked Collins. "The missile should be within range in a few seconds," he responded. Warren decided to continue the attack on the first missile since they were so close to firing. Seconds later the laser fired, taking out the first missile, and the system locked onto the next missile. Although the system had hooked onto the target and the missile was within range, the laser still did not fire.	**Decision:** Abort firing on the first missile to try to shoot down the other two missiles? **Cues:** Prioritization (type of missile, angle of the missiles, launch site, projected impact point, do any of the missiles carry weapons of mass destruction, battle management mode, commander's intent), time (is there enough time to shoot all the missiles before they burn out), chances of shooting down all missiles (what missile do you have the best chance of shooting down)
Collins noticed that the missile was coming towards the Airborne Laser at an angle that made it almost impossible to lock onto. *I don't think there's enough time to lock onto the next missile, my best bet is to stay with this one and hope it levels out in time*. At the last moment the missile changed trajectory and the laser shot it down. Meanwhile, the third missile had burnt out. They were able to shoot down two of the three missiles. *We should've had that one* thought Collins as he estimated the projected impact point of the leaker. Warren reported the results and projected impact point to Airborne Command and Control and the rest of the crew resumed preparations for the next launch.	**Decision:** Determine why the laser is not firing **Cues:** The missile is at a bad angle and the system cannot lock onto it

The story demonstrates the usefulness of a scenario as a tool to illustrate the cognitive requirements in context, and provides a platform for understanding the implications of different cognitive and team requirements. For example, variables such as staff size, the assignment of responsibilities (including decisions), and coordination could be manipulated to determine the effect on a particular mission. The use of scenarios is the basis of a tool proposed for follow-on development.

Human-Computer Interaction Recommendations

These suggestions are based on the decisions elicited for the Battle Management Crew. They are briefly described in the "Additional CTA Data" column of the Cognitive Challenges tables in Appendix A. These tables make explicit the decisions on which the suggestions are based. Some of these recommendations are to add functionality or concepts to the displays. These recommendation are designed to alleviate some of the cognitive challenges and make the tasks and decisions more manageable. Other recommendations are based on our observations of how the operators used the technology during the JEFX-99 simulation. These are suggestions for modifications of the system and screen displays. We recognize one main purpose of the ABL participation in the simulation was to test these displays and that they may have already been modified. Nevertheless, we believe these recommendations will be helpful in making the displays more decision-focused. A third type of recommendation is to keep display concepts used during JEFX-99. These display concepts were observed to be helpful in accomplishing some of the tough decisions. The numbers correspond to numbers in the tables in Appendix A.

[1.1] Include designators for tracks. During the simulation, poor designators caused operators to refer to "that guy over there in the north sector." The more specific the operators can be in their communication, the better they will be able keep situation awareness of the enemy.

[1.7] Put circles around the Surface to Air Missile (SAM) sites that indicate the range missile effectiveness. This will give operators a visual representation of the areas that should be avoided. It will help operators gauge the threat to the ABL by making at least one potential threat readily apparent.

[2.2] Operators need to be able to filter and sort track information quickly. At a basic level, operators need to differentiate between tracks and be able to turn them on and off. In order to maintain the big picture, the operators should be able to access every kind of track -- surface, air, ground, and subsurface. Operators also need to be able to choose which tracks to leave on. In order to do this quickly, the track selection options should not be deeply embedded within menus. One option is to have categories from which to select, similar to the AWACS category select switch.

[2.5] Allow operators to put their own designators on tracks. For example, if an operator becomes suspicious of an enemy air track that is headed in the direction of the ABL, the operator could turn that track a different color or put a circle around it to easily and quickly locate the track on the screen. This will help operators keep track of potential problems.

[2.7] Allow operators to switch configurations between the crew without re-logging on as a new user (which can take precious time). For example, if one crew member is temporarily filling in for another, that crew member could temporarily switch configurations to see either the big picture (zoomed out with more tracks active) or a more narrow picture (zoomed in with only the air tracks active) depending on the situation.

[2.9] Have the high value assets (HVA) stand out on the screen so they are easily recognized. The ABL is dependent on one HVA, the AWACS, for much of its information; it is important that the operators be able to quickly locate HVAs. During the simulation one of the operators kept asking for track history. When asked why he wanted the history, he replied that he wanted to know where the AWACS was and track history would tell him this. The operator didn't need track history, he merely needed to know the location of HVAs. The standard designator of a HVA could be a green circle around the track.

[2.18] Create an automated Air Tasking Order (ATO) that operators could access from their displays. For each mission print out a "cheat sheet" that includes the call signs, modes, and codes. This is a lot of information to keep in memory and call upon when needed. These aids would assure that the information is there when the operators need it. In addition, provide a desk or writing area at each workstation so operators can store this information and make any notes that are necessary.

[3.3] If the system ever contains an automatic function that provides flight directions (changes to orbit, changes to position in orbit) to the Flight Crew, this information also needs to be provided to the Battle Management Crew. The Battle Management Crew will use this information to determine if they are ready to respond to missile launches, and to monitor their location in the orbit.

[3.5] Have the system record information on individual missile launches such as time of launch, location, track number, actions taken, and results. Allow the user to access either information on individual launches or a summary of recent launches. This will help the user detect patterns and determine trends of launches.

[3.6] Include a function in which the system takes the information generated in [3.5] and predicts the location of future launches. It is important, not just to provide the predictive data, but to allow the user to

access the raw data so the user can use his/her experience to look for trends and patterns. This information can help the ABL crew determine the optimal orbit placement.

[3.8] Include a function that can calculate the range between objects. For example, if the user selects the ABL track and then selects another track, the system will provide the distance between the two objects.

[5.2] Add a function to the system that would use information such as anticipated launch sites, current orbit, current threats to ABL, and priorities to calculate and recommend the optimal orbit.

[5.3] There are many reasons that the system will not fire in automatic mode. Inability to acquire the target, the missile is no longer in the boost phase, a conflict with another aircraft or satellite, or the presence of a higher priority target are a few examples of why the system may not fire. When the system cannot fire, it is important that the operator know the reason. The system could display a brief message such as "Missile out of boost phase" or "Conflict." It is very important that the operator understand the system's reasoning. If not, the operator could switch to manual mode and proceed with the shot anyway. It there is a conflict and the operator fires in manual mode, the results could be disastrous. Another way to avoid firing when a conflict exists is to display the word, "Conflict" and have the conflict blink on the screen so the operator does not fire until the conflict is resolved.

[5.6] Allow the user to easily determine how long it will be until the end of the orbit is reached. If the user could simply click on the end of the ABL orbit to determine the range and the estimated time until arrival, this information could be used to determine if the aircraft was optimally placed to respond to missile launches. Many times during JEFX-99 we heard the operators ask the pilot for this information and adjust the aircraft position based on that information. The system should specify whether the results are in miles or kilometers.

[6.1] Currently in manual mode the operator must perform deconfliction. This is a challenging task because the operator must combine information from one display that shows altitude and another display that shows the bird's eye perspective of the battlefield. There is not a one-to-one correlation between the displays and some transformations must be performed to understand the three-dimensional space and determine if there are conflicts. One solution is to show the two displays from the same perspective. Currently the altitude display is shown from the perspective of the ABL so as the ABL turns, the picture changes. However, the bird's eye view display is shown independent of ABL movement. In other words, on the altitude display the ABL stays in place and the other tracks move around it and in the bird's eye view display the ABL moves as well as the other tracks. Another solution is to incorporate a

deconfliction warning in manual mode. The operator could still decide to take the shot but a warning message would appear and the conflict would blink on the screen.

[6.7] When a missile is launched, dim all the other tracks so the missile is easily noticed. This way the other tracks can still be seen but the missile track will stand out. During the simulation, the operators had trouble finding the missiles on their screen during a launch. The missile would initially blink but if the operator missed that signal, the missile could become hidden in the other screen clutter. One operator developed a workaround to compensate for this. Every time the audio alarm signaled a launch the operator would clear all tracks to easily isolate the missile.

[7.13] When a missile is launched the operator may want to zoom out or zoom in to get a better picture. These functions should be easily accessed by buttons on the screen without having to access detailed menus. Another idea is to have a "back" zoom button that reverts to the last magnification. This would allow users to toggle between two relevant magnifications.

[7.15] When a missile is splashed, display the track number on the screen for a longer period of time and allow this information to be accessed later. During the simulation the track number would sometimes disappear from the screen before operators could read it.

TIDE Analysis of Airborne Laser Crews

This section describes the results of the TIDE analysis on ABL. One purpose of the analysis was to determine optimal crew configuration including crew size and assignment of roles and responsibilities. The other purpose was to ascertain the usefulness of TIDE for the project manager tool.

The tasks were allocated to the five crew members (Mission Crew Commander or MCC, Air Surveillance Officer or ASO, Weapon System Officer or WSO, Technician, Pilot) based on the current descriptions of the ABL concepts of operations. Relative workload for each crew member was calculated across time for the mission functions. Figure 6 presents the workload profiles for each of the crew members and the pilot. Note, this measurement of workload was relative due to the lack of detailed information about the tasks.

As you can see in this figure, the current task/personnel assignments result in the ASO carrying a much larger workload than the rest of the crew members across all overall tasks, particularly in the missile elimination tasks. The MCC has peaks of relatively heavy work load during self defense tasks, and the WSO and technician remain relatively low in workload throughout the mission. As expected, the WSO's

workload increases during the missile elimination task, and the technician's workload rose in response to system and laser failures.

The current crew/task assignment was then examined to determine where improvements could be made to more evenly distribute the workload. The primary objective was to lower the ASO's relative workload level and level the workload distribution across the entire team. Much improvement was achieved by assigning exclusively to the MCC many of the tasks for which the MCC and ASO had previously shared joint responsibility. A second major improvement resulted from the allocation of the ASO's deconfliction tasks to the WSO. As with the MCC's assignments, most of the tasks assigned to the WSO had previously been the joint responsibility of the ASO and the WSO. After reallocating the tasks within the team, workload of all crew members was recalculated, as shown in Figure 7. As can be seen, the reallocations resulted in a more evenly distributed workload among crew members.

The research team decided to initiate a second task allocation process to explore the possibility of reducing the number of organization members (three-person crew plus pilot). Based on a workload analysis, the tasks of the technician were to be reallocated to the other crew positions. The WSO was assigned several of these tasks, as they overlapped with many of his or her duties. The initial iteration of the reduced staff design yielded a relatively overloaded WSO. In the successive iterations, we aimed to optimize the workload distribution of the reduced staff crew. In a second iteration, the pilot was assigned tasks from the WSO (Monitor cap location) and tasks from the ASO (Tasks related to self defense monitoring). The result of these reallocations was an improvement in both the WSO's and ASO's workloads, but a pilot who was at times relatively overloaded (particularly when the ABL was under attack). In the third iteration, the pilot's task load was reduced and focused primarily on the WSO's former duty of "Monitor CAP location." The result of this was a much more evenly distributed workload throughout the aircraft. Figure 8 presents the workload profiles for the final reduced staff organization.

In our Phase I SBIR work, we demonstrated that the TIDE team-design process was able to provide insight regarding where and how members of the ABL crew are likely to be overloaded under the current team configuration. We also showed how the TIDE process can be used to generate a new team design that balances the workload more evenly across the five-person ABL crew. Finally, we explored the possibility of reducing the ABL team size from five to four, and concluded that this would result in possibly unacceptable overload of the WSO position under the current distribution of tasks. When tasks were reallocated, using an algorithm to balance the workload across crew members, however, we were able to produce a reduced-staff team design that accomplished the tasks without overly burdening any of the crew members.

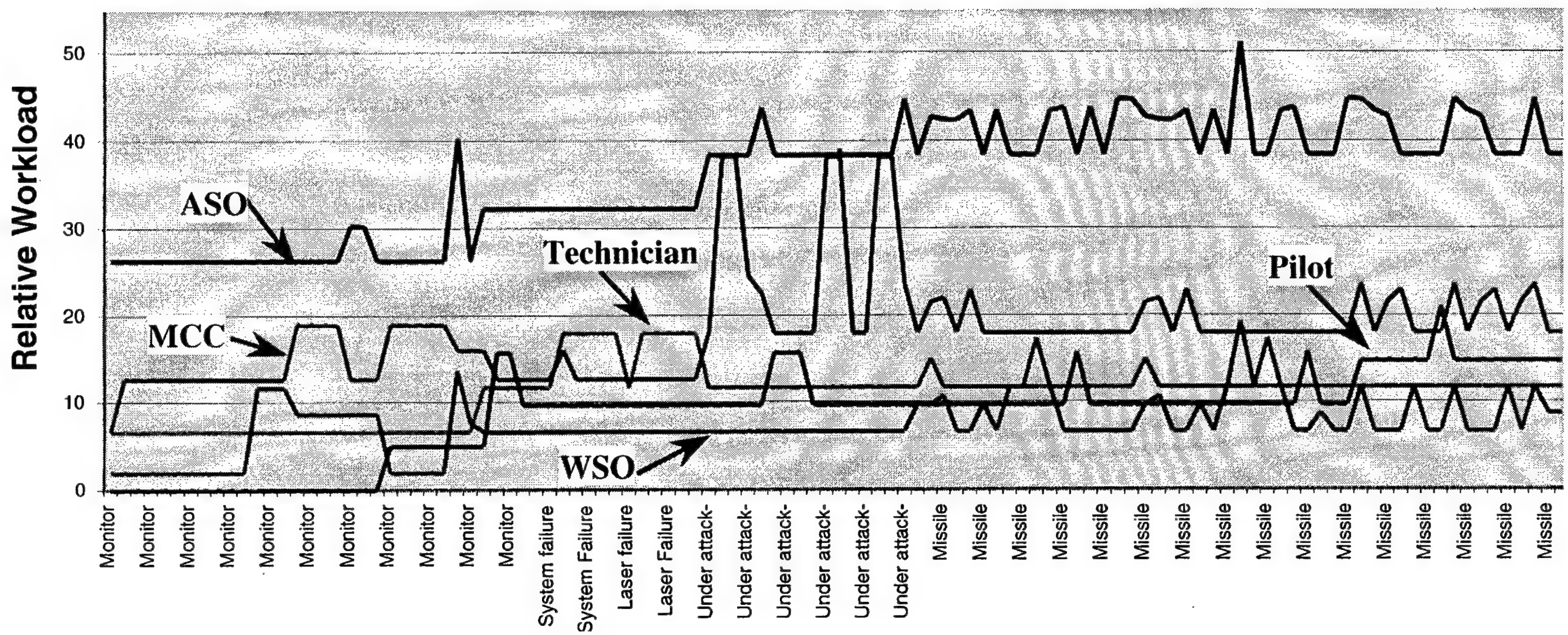

Figure 6. Initial workload profiles of current four-operator crew and pilot.

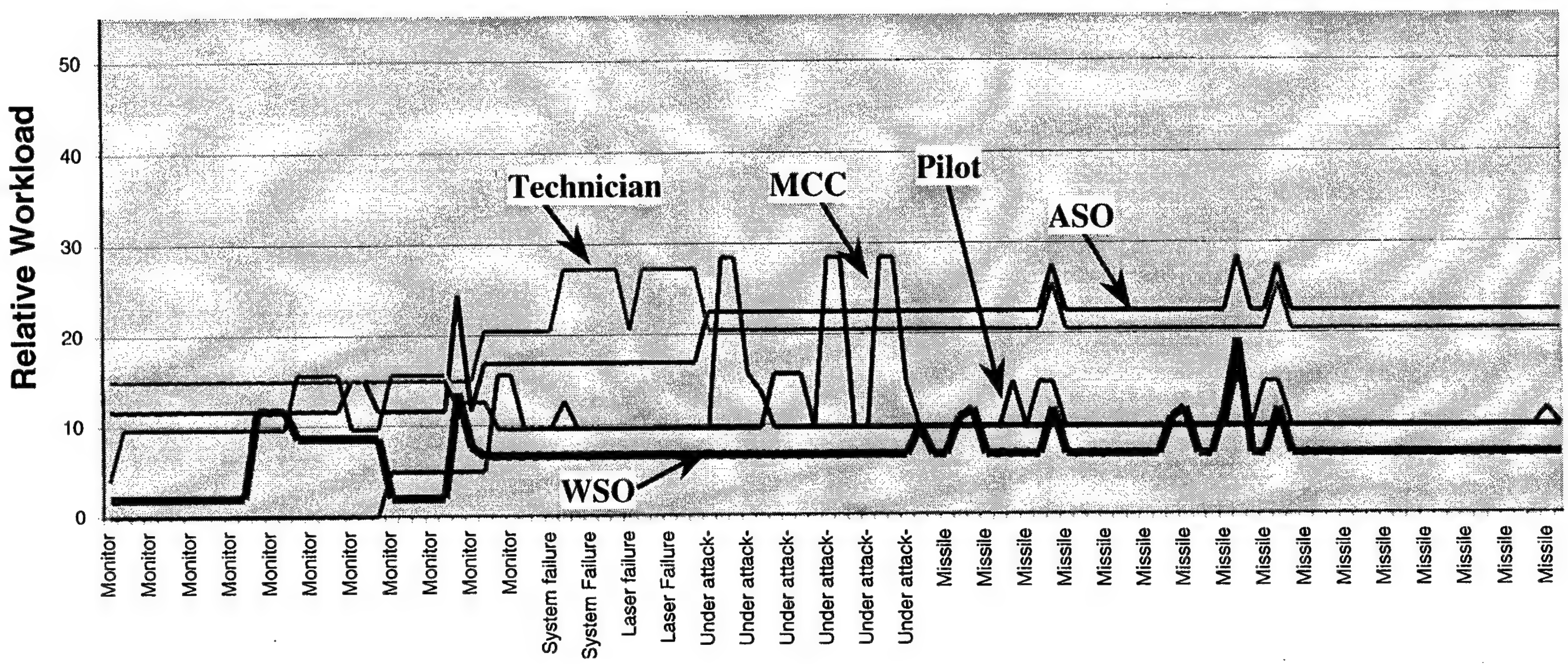

Figure 7. Workload profiles of crew and pilot following task reallocation.

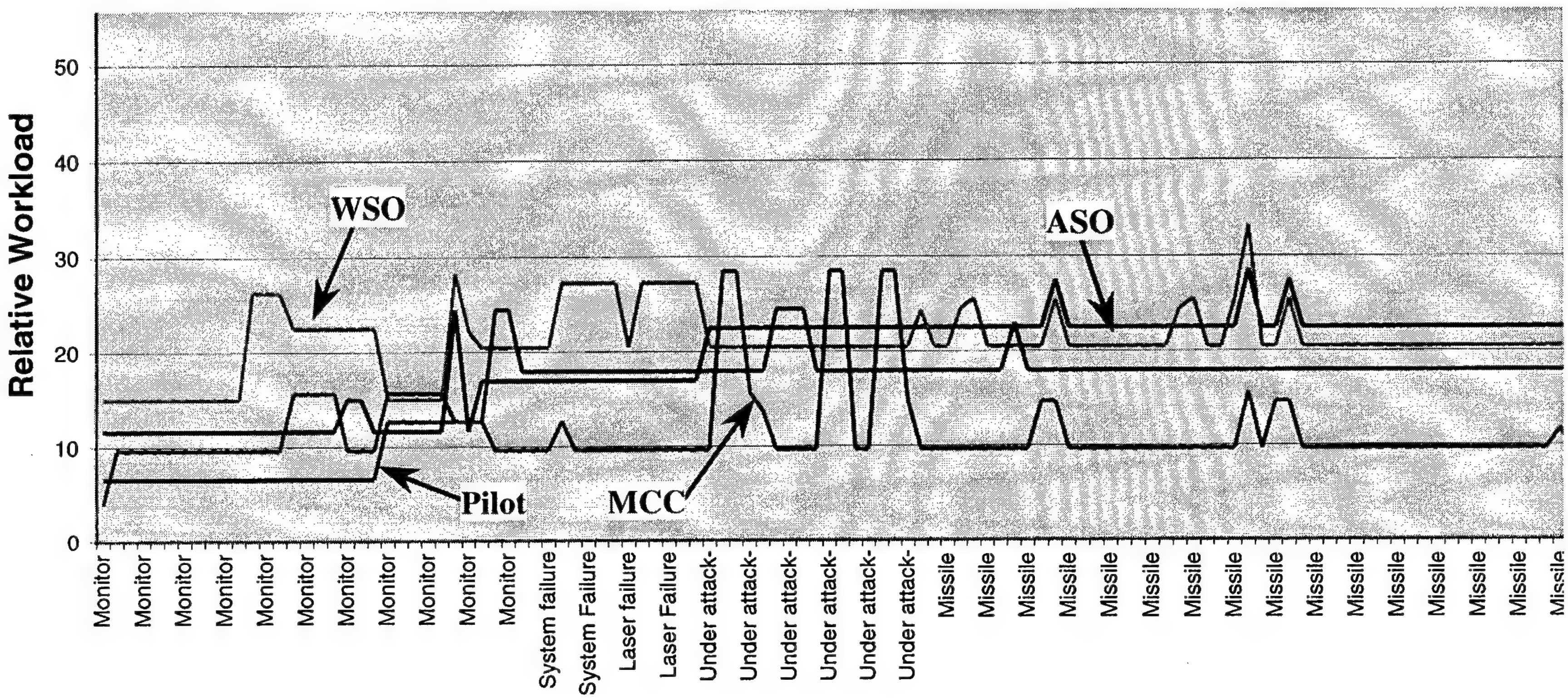

Figure 8. Workload profiles of reduced crew organization: Final iteration.

CONCLUSIONS

As previously stated, cognitive engineering does not adequately address the decision making or team aspects of users in the development of new systems. For this reason, the objectives of this effort were to:

- target Program Managers who could use these cognitive requirements early in the design phase, rather than system engineers
- use a decision-centered approach rather than focusing on procedures
- study the emergent properties of teams rather than focusing on individuals

We were able to successfully demonstrate the effectiveness of the above concepts. The first two objectives were demonstrated within the context of ABL. We were able to elicit and present information about the critical judgments, decisions, information needs, and coordination issues involved in the ABL mission and organize these into major functions of the Battle Management Crew. We illustrated several team coordination issues in the decision scenario. A next step could be to distribute the decisions within each major function to the different crew members. Taking a decision-centered approach to task allocation and assignment of roles and functions has several benefits. It will be clear which crew member is responsible for each decision, and how team members can support other crew members' decision-making. In addition, since the division of roles is based on an analysis of the team, emergent properties such as coordination and information flow will not be overlooked.

We were able to demonstrate the utility of our third objective through interviews with Program Managers. All four Program Managers indicated that information about the user, including decision making and team aspects, was critical. Program Managers need this information early in the design process. Ideally the information would be provided in time to affect the concept of operations. If cognitive and team requirements can be incorporated into the concept of operations, both time and money can be saved. The Program Managers expressed disappointment that mature tools to provide this information did not exist. One Program Manager emphatically expressed that he did not want human factors "expert opinion," he wanted an audit trail to trace the origin and reasons behind recommendations involving the user.

Future Research Ideas

In addition to demonstrating the feasibility of our objectives, we were able to develop an approach to integrating these ideas into a comprehensive tool. Our approach would be to develop a prototype tool that enables Program Managers to apply cognitive engineering early in the conceptual phase of system design.

Most of the key design decisions are made at the beginning of the effort, at a point where there are few opportunities to run studies and collect data on individual and team performance. As a result, cognitive requirements tend to be ignored until relatively late in the cycle. Our intent is to turn that around, by providing a platform for considering individual and team cognitive requirements from the start.

The target user of the tool would be Program Managers and directors of engineering, along with the using command sponsors of the development effort. We believe that the tool will be helpful for the design engineers working on the system, but the primary audience would be at the level of management -- to conceptualize the dynamics and tradeoffs that involve cognitive tasks.

The prototype tool is called *Cognitive Requirements for Individuals and Teams: Evaluations, Recommendations, Integration, and Analysis* (CRITERIA). The intent is to define and represent the cognitive criteria for tasks involving information technology and command and control (as opposed to physical criteria such as reach envelopes). The tool will address both individuals and teams, but not organizations. The tool will not contain automated analysis. Our judgment is that automated analysis is not sufficiently mature for our needs. Instead, CRITERIA will function as a guide in collecting and representing cognitive engineering considerations so that Program Managers can consider the implications of different configurations.

CRITERIA will include a graphic display of team configurations to show how alternative configurations would handle different types of situations. This is the central aspect of CRITERIA. Decision scenarios will be developed to present challenges to the individuals and to team coordination, and CRITERIA will illustrate how these challenges would be handled by teams varying in size and qualifications. That is how alternative recommendations would be identified and evaluated early in the design cycle. The decision scenarios and recommendations would be based on Cognitive Task Analysis with subject matter experts performing analogous types of work, and adapting the findings to fit the constraints of the envisioned situation.

CRITERIA is not intended to provide comprehensive answers about team configuration questions. During the early stages of concept development, there are simply not enough data and the goals are too ill-defined. Instead, CRITERIA is a tool to assist Program Managers in thinking about the issues and understanding the tradeoffs. We are drawing on the work using decision scenarios (e.g., Schwartz, 1991) as a means of learning about dynamics, rather than arriving at answers.

CRITERIA will have another benefit, which is to enable Program Managers to define a concept of operations. The graphic representation of team interactions, built around the results of Cognitive Task

Analysis, will permit the designers to conduct what-if analyses, and to describe preliminary concepts of how the system will be used once it is fielded. The concept of operations will contain initial recommendations for staffing (number, specialty, training requirements) including command and control considerations and team coordination issues, as well as logistical support requirements (if these are included in the scenarios). We recognize the wide range of competing demands placed on Program Managers, and we can see how easy it is for attention to be focused on hardware and budgetary concerns. Therefore, we believe that it is important for CRITERIA to assist Program Managers in tackling essential parts of their responsibilities (such as developing a concept of operations) to encourage its use in exploring cognitive requirements.

Major steps towards the design of CRITERIA have been accomplished during the Phase I SBIR effort. We have conducted observations and interviews to determine the functionality needed. We have also explored the use of advanced discrete event simulations, and determined that the existing systems would not be helpful because of the limited amount of data available early in system design. We determined that the focus of CRITERIA needed to be a graphic representation showing how individuals and teams would manage different types of challenges during operations, so that Program Managers could discover for themselves the strengths and limitations of alternative crew configurations. We have also defined the types of Cognitive Task Analysis data needed to define the decision scenarios.

We believe that the tool, CRITERIA, will be unique in the type of capability it affords Program Managers to insert cognitive requirements early in the design cycle. We further believe that CRITERIA has the potential to result in a revolutionary change in system development. As the Air Force draws upon information technologies for more and more applications, the need to address cognitive engineering issues will grow, and the value of CRITERIA will increase.

This page left blank intentionally.

BIBLIOGRAPHY

Hutton, R. J. B., Anastasi, D., Thordsen, M. L., Copeland, R. R., Klein, G., Serfaty, D. (1997). Cognitive function model: Providing design engineers with a model of skilled human decision making (Contract No. N00178-97-C-3019 for Naval Surface Warfare Center, Dahlgren, VA). Fairborn, OH: Klein Associates Inc.

Klinger, D. W., Andriole, S. J., Militello, L. G., Adelman, L., Klein, G., & Gomes, M. E. (1993). Designing for performance: A cognitive systems engineering approach to modifying an AWACS human-computer interface (Contract AL/CF-TR-1993-0093 for Department of the Air Force, Armstrong Laboratory, Air Force Materiel Command, Wright-Patterson AFB, OH). Fairborn, OH: Klein Associates Inc.

Klinger, D. W., & Gomes, M. G. (1993). A cognitive systems engineering application for interface design. Proceedings of the Human Factors Ergonomics Society 1993 Annual Meeting, 16-20, Santa Monica, CA: HFES.

Klinger, D. W., & Klein, G. (1999). Emergency response organizations: An accident waiting to happen. Ergonomics In Design, 7(3), 20-25.

Klinger, D. W., Thordsen, M. L., & Copeland, R. R. (1998). A cognitive task analysis of surveillance personnel onboard AWACS aircraft (Final Technical Report Contract P.O. P3805, Prime Contract F41624-95-D-6026). Fairborn, OH: Klein Associates Inc.

Landauer, T. K. (1995). The trouble with computers: Usefulness, usability, and productivity. Cambridge, MA: MIT Press.

Miller, T. E., & Lim, L. S. (1993). Using knowledge engineering in the development of an expert system to assist targeteers in assessing battle damage and making weapons decisions for hardened-structure targets (Contract DACA39-92-C-0050 for the U.S. Army Engineers CEWES-CT, Vicksburg, MS). Fairborn, OH: Klein Associates Inc.

Norman, D. A. (1991). Cognitive science in the cockpit. CSERIAC Gateway, 2(2), 1-6.

Schwartz, P. (1991). The art of the long view. New York, NY: Doubleday.

Stottler, R., & Thordsen, M. L. (1997). Artificial intelligence techniques for the Pilot Approach Decision Aid Logic (PADAL) System. Final report prepared under Contract No. 68335-96-C-0205 for Naval Air Warfare Center, Aircraft Division, Lakehurst, NJ.

Vicente, K. J. (1999). Cognitive work analysis: Towards safe, productive, and healthy computer-based work. Mahwah, NJ: Erlbaum.

Woods, D. D., Johannessen, L. J., Cook, R. I., & Sarter, N. (1994). Behind human error: Cognitive systems, computers and hindsight (CSERIAC SOAR 94-01). Wright-Patterson Air Force Base, OH: Crew Systems Ergonomics Information Analysis System.

GLOSSARY OF ACRONYMS

ABL	Airborne Laser
AFSC	Air Force Specialty Codes
ASO	Air Surveillance Officer
ATO	Air Tasking Order
AWACS	Airborne Warning and Control System
BMC4I	Battle Management Command, Control, Communications, Computers, and Intelligence
CAP	Combat Air Patrol
CRITERIA	Cognitive Requirements for Individuals and Teams: Evaluations, Recommendations, Integration and Analysis
CTA	Cognitive Task Analysis
DCD	Decision-Centered Design
HVA	High Value Assets
JEFX-99	Joint Expeditionary Force Exercise 1999
MCC	Mission Crew Commander
SAM	Surface to Air Missile
SBIR	Small Business Innovative Research
TIDE	Team Integrated Design Environment
WSO	Weapon System Officer

This page left blank intentionally.

APPENDIX A

A DESCRIPTION OF THE COGNITIVELY CHALLENGING ASPECTS OF THE ABL MISSION

This page left blank intentionally.

Table A-1: Self Protection

Decision/function	CC*	Why challenging?	Additional CTA data
1.1 Monitor enemy tracks	Med.	There are multiple tracks which can disappear and reappear. The enemy will often be trying to use deception so operators need to maintain enemy perspective to make sense of what they see on the screen. Tracks can carry weapons that can be a threat from farther away than the original track itself. Need to project ahead and understand implications of enemy actions.	Some classes of MiGs (MiG 25 and 31) can fly high and are difficult to intercept, even for F-15s. Display fix – include designators for tracks.
1.2 Monitor CAP location	Low	This is a visual and auditory task – monitor tracks or radar and monitor communicates between CAP & AWACS. It may become more challenging if CAP has been vectored off somewhere where they could become confused with other tracks.	Need to be able to listen to control frequencies between AWACS and CAP for advanced "I &W" (threat status, leakers, whether they got all the hostiles).
1.3 Determine if sensors and communications are working	High	Must notice inconsistency in data. In other words, you need to see what is not there. Indicators may not reflect exactly what the system is actually doing. It is easy to assume that information is being sent and received if there are no indicators to let you know something is <u>not</u> working.	

* CC stands for Cognitively Challenging

Table A-1: Self Protection (continued)

Decision/function	CC	Why challenging?	Additional CTA data
1.4 Determine when to retrograde and where	Med.	Need to project ahead and determine when is it too late to retrograde according to time distance affordances. Much of this task is procedural and specified in the Air Tasking Order with specific parameters outlined. Difficulty may occur if there are different parameters depending on the threat and if the threat has not been positively identified. (E.g., orders to retrograde if a certain type of hostile aircraft gets within xx miles, but provided information is insufficient to determine what type of aircraft is approaching.)	
1.5 Determine mission go/no-go	Med.	There is external pressure to continue mission. Involves early problem detection.	If JTIDS is not working, the situation may be a mission no-go. Parameters would be specified in the ATO.
1.6 Determine range from threats	Low	If the Link data from AWACS, JSTARS, Intel, and I&W is accurate, this should not be difficult.	
1.7 Gauge threat to Airborne Laser	Med.	Requires identification of the type of threat. Hostile aircraft can carry different kinds of missiles and it is the missile more than aircraft type that can be the determining factor. Need to anticipate enemy action, think ahead, and estimate CAP's ability to respond (time, distance factors).	Display aid – put circles around Surface to Air Missile (SAM) sites indicating the range of their missiles. There is a need to know immediately whether all the hostiles were stopped. The crew may know ahead of time (from intelligence) that the Airborne Laser is a target.

Table A-1: Self Protection (continued)

Decision/function	CC	Why challenging?	Additional CTA data
1.8 Monitor defensive air ops for threats and potential engagements	Med.	There are competing information sources and attention management issues. Requires attention to be focused on the defensive air ops to hear what they are doing and judge potential threats.	Might require an additional communications channel to listen on defensive air ops communications.
1.9 Know whether Airborne Laser is a target that day	Low	Requires declarative knowledge. This is information the enemy would strive to keep hidden. Therefore, it may be difficult to determine.	May have to assume that Airborne Laser is always a target on any particular day.
1.10 Anticipate CAP refueling	Med.	Must think ahead while performing current tasks, dependent on several factors – time, weather, orbit, etc. Involves communication with CAP. This issue covered the pre-mission briefings.	
1.11 Decide to shoot enemy aircraft	Med.	Must be done in manual mode so deconfliction must be performed with other aircraft and satellites.	May involve visual identification.
1.12 Request to shoot enemy aircraft	Low		

This page left blank intentionally.

Table A-2. Maintain Plan Flow

Decision/function	CC*	Why challenging	Additional CTA data
2.1 Monitor enemy tracks	Med.	There are multiple tracks that can disappear and reappear. The enemy will often be trying to use deception so operators need to maintain enemy perspective to make sense of what they see on the screen. Tracks can carry weapons that can be a threat from farther away than the original track itself. Need to project ahead and understand implications of enemy actions.	
2.2 Filter and sort information	High	Need to make meaning and draw conclusions from the information (synthesize). If information is ambiguous, missing, or incorrect, it can make filtering and sorting difficult. If too much information is coming in, it can be difficult to identify which information is relevant.	Operators need to filter the information that is displayed. All data blocks are not the same; it depends on the track. For example, altitude is not necessary for ground and surface tracks. Modes and codes are not necessary for all tracks.
2.3 Determine whether sensors and communications are working	High	Must notice inconsistency in data. In other words, you need to see what is not there. Indicators may not reflect exactly what the system is actually doing. It is easy to assume that information is being sent and received if there are no indicators to let you know something is <u>not</u> working.	

* CC stands for Cognitively Challenging

Table A-2. Maintain Plan Flow (continued)

Decision/function	CC	Why challenging?	Additional CTA data
2.4 Determine where strikes are taking place	Low	Information is available in the Air Tasking Order (ATO) and on the screen.	A maneuvering surface to air missile (SAM) suggests a strike package is taking place.
2.5 Detect problems and inconsistencies in track data	High	This is dependent upon the number of sensors you have out there, the sensitivity of the sensors, and the location of the sensors. Inconsistencies may not stand out, or they may occur frequently enough that the important ones do not stand out more than the unimportant ones. Need experience base to compare situation and recognize anomalies.	Display aid – a tool could be built to track certain aspects during critical salient events. It is difficult to maintain situation awareness and not narrow your focus during a critical event. A display aid could show relevant information without distracting the operator from the focus.
2.6 Know and apply commander's intent	High	Involves applying commander's intent to the current situation and determining if your actions are consistent. This can be difficult if the commander's intent is poorly articulated or focused at the wrong level of granularity.	
2.7 Switch configuration between users	Low	Need to determine the level of information you need to know (big picture versus specifics).	This needs to be done quickly without relogging in as a new user. If the display and its accompanying switch actions to do this task are complex and deeply embedded in menus, it can make the task much more difficult.
2.8 Perform spatial and audio discrimination between voice communications	Low	Need to determine who is speaking (source of information) at the same time you are listening for relevant information.	

Table A-2. Maintain Plan Flow (continued)

Decision/function	CC	Why challenging?	Additional CTA data
2.9 Monitor location of high value assets (HVAs)	Med.	Can be difficult if, for security reasons, the locations of the HVAs are not widely disseminated. Some individuals on Airborne Laser may not have high enough clearance to be entitled to this information. Note: "standard" HVAs shouldn't pose too much of a problem since they should be readily visible on the displays (e.g., AWACS, JSTARS, RJ, EA-6B, etc.).	Display aid - have the HVAs stand out by placing a circle around them or using a different color.
2.10 Monitor track number changes	Med.	Need to integrate information from multiple sources. If the track number changed, the operator may need to unlearn the old number as well as learn the new number.	It is possible that tracks may be picked up by multiple sensors, especially in joint operations (e.g., by a US AWACS, a NATO AWACS, an E-2C, an AEGIS cruiser). Given the possibility for multiple sensors to acquire the track, there is a need for all of these linked data sources to be "correlated." There is a greater chance that tracks can be given multiple track numbers until the system sorts out what's actually out there. As a result, there could be situations where a track number could be changed. One difficulty with track number changes is that operators often type in the track number of interest (once they 'learn' it) and a change in numbers can have them inadvertently looking at the wrong track.

Table A-2. Maintain Plan Flow (continued)

Decision/function	CC	Why challenging?	Additional CTA data
2.11 Monitor defensive air ops for threats and potential engagements	Med.	There are competing information sources and attention management issues. Requires attention to be focused on the defensive air ops to hear what they are doing and judge potential threats.	Might require an additional communications channel to listen on defensive air ops communications.
2.12 Determine which links to leave on	Med.	One challenge is to determine what information is needed and anticipate future information needs, to maintain SA. Another challenge is to figure out which data source is the accurate one. Almost every source believes they are sending accurate information.	
2.13 Input and output the order of battle	Low		
2.14 Monitor voice product net for C2 information	Med.	Requires attention to monitor. Criticality, importance, and implications of information may not be obvious so it may require additional analyses to interpret.	
2.15 Keep the team engaged and alert to the possibility of missile launches	Med.	Crew will need to keep vigilance and prevent complacency or boredom. The crew needs to maintain situation awareness in order to act immediately when a launch occurs.	One estimate is that 95% of the time the crew will be inactive.
2.16 Edit automatic prioritization matrix	Low		
2.17 Update pilot (enemy location, status)	Med.		

Table A-2. Maintain Plan Flow (continued)

Decision/function	CC	Why challenging?	Additional CTA data
2.18 Reassign tasks/orchestrate priorities	High	This is a resource allocation issue. It is difficult to determine priorities when everything is important. This must be done on a minute-by-minute basis.	One strategy is to ask how long a task will take and determine if there is something that should be done in the meantime.
2.19 Know the players call sign, modes, and codes	Med.	This is a lot of information to commit to memory and call upon when needed.	Display aid – an automated ATO or cheat sheet.
2.20 Anticipate refueling	Low	Involves projecting into the future to determine need.	

This page left blank intentionally.

Table A-3. Aircraft Placement

Decision/function	CC*	Why challenging	Additional CTA data
3.1 Determine placement of orbit	Med.	This is a tradeoff because the Airborne Laser needs to be close enough to pick up launches but far enough away so as to not be constantly at risk by SAMs, hostile aircraft, or other enemy threats.	
3.2 Determine type of orbit (circle, figure eight)	Med.	Need to develop new strategies to maximize the time pointed towards threat areas and to place the Airborne Laser close enough to threats that they can acquire and shoot missiles down before they burn out.	Placement of orbit is driven by: terrain (mountains, tree canopy), assets, threat, battle management mode, whether the Airborne Laser is a target, status of weapon system, etc. Will probably need to consider some additional geometrical orbit configurations. Initial orbit configurations seem to be based on those flown by AWACS & JSTARS and these may not be good base models for determining the Airborne Laser's ideal orbit for a particular mission.
3.3 Monitor position in orbit & range of fire	High	Involves anticipating launches (thinking ahead) and determining where the aircraft will be during critical events. In addition, their priorities (possible launch areas) need to be factored into orbit design, and these can be conflicting priorities. Involves tradeoffs between optimal fire position and safety of ABL	Display fix – any automatic directions to the Battle Management Crew as well as the flight crew.

* CC stands for Cognitively Challenging

Table A-3. Aircraft Placement (continued)

Decision/function	CC	Why challenging?	Additional CTA data
3.4 Determine how long it will take to reach the end of orbit	Med.	This requires time-space calculations that are difficult to perform mentally with great accuracy.	
3.5 Determine trends of launch locations	Med.	Need to remember and integrate launch locations as well as context of the launch (time, situation, threat level) to identify trends. When does something become a pattern?	Display aid – The system could summarize information on launches and present this to the user. Once you identify a "trend," do you move the Airborne Laser and commit yourselves to this trend? How conservative do you want to be?
3.6 Anticipate future launch sites	Med.	Involves identifying trends, projecting ahead, and thinking like the enemy.	Display aid – The system could predict future launch sites and the likelihood of their occurrence.
3.7 Gather intelligence on predicted launches	Low		Real time (and accurate) intelligence may not be able to be disseminated in enough time for it to be beneficial.
3.8 Recommend changes in orbit or speed	Med.	Requires consideration of multiple factors to determine if there will be an advantage to changing the orbit. (Anticipated launch/target sites, current orbit, threats to Airborne Laser, priorities, etc.)	The aircraft may already be in a right bank although you need to turn left. It may be quicker to keep turning right even though it is the longer route. Display aid – the system could help calculate this information and recommend orbit changes.

Table A-3. Aircraft Placement (continued)

Decision/function	CC	Why challenging?	Additional CTA data
3.9 Request change in orbit placement	Low	Need to time the request so the person who makes the decision hears it.	It may be difficult to reach someone who has authority to approve orbit placement changes. A change in orbit placement is a commitment. It means moving away from an area that, at least at one time, was considered a good place to be.
3.10 Monitor defensive air ops to determine threats	Med.	There are competing information sources and attention management issues. Requires focused attention on the defensive air ops to hear what they are doing and judge potential threats.	Might require an additional communications channel to listen on defensive air ops communications.

This page left blank intentionally.

Table A-4. Determine System Status

Decision/function	CC*	Why challenging	Additional CTA data
4.1 Determine quality of data (timely, accurate)	High	[Processed data may be enhanced by the computer and mask quality so operators need to be able to notice subtle cues.] Operators need experience and a baseline to develop expectancies and notice violations. Delays in system processing can effect timelines. Often there is not enough time to go back to the source and confirm information.	The source can impact decisions. For example if the source is ground radar, there are certain things that they cannot see so that data may not be as credible. If multiple tracks are reported, and they are from the same source, it is likely that multiple tracks actually exist. However, if the multiple tracks are reported from different sources, they may actually be the same track reported twice.
4.2 Determine confidence in data	Med.	The source can alter confidence and the source may not be obvious. The operator may not know what transformations have been performed on the data.	Display aid – The source of the information could input confidence fields (1-4 with 1 being slightly confident and 4 being very confident) and update these as necessary. The Airborne Laser operators could then have access to these confidence fields. An operator needs experience and knowledge in air theatre to determine whether the source is in a position to "see" the information. You need "smart ears." Sometimes you want to see data as well as hear it.

* CC stands for Cognitively Challenging

Table A-4. Determine System Status (continued)

Decision/function	CC	Why challenging?	Additional CTA data
4.3 Assess whether the systems are working	Med.	The system may mask the problem. May need to pick up on subtle cues or interact with the system to detect problems.	
4.4 Determine if the laser is working	High	This is a new system and operators will not have an experience base.	Will require input from technician.
4.5 Maintain a mental model of system and affordances (system capabilities and limitations)	Med.	Need to integrate information from multiple sources to form a larger mental model. Requires intimate understanding of the system.	
4.6 Determine which data are better (more timely, accurate)	Med.	Involves conflicting information. May not be able to determine source. Requires information about the "age" of the data, which may be difficult to obtain.	

Table A-5. Readiness to Shoot

Decision/function	CC*	Why challenging	Additional CTA data
5.1 Determine if the aircraft is turned the correct way	Med.	Involves anticipating launches (thinking ahead) and determining where the aircraft will be during critical events. In addition, priorities (possible launch areas and/or anticipated NAIs) need to be factored into orbit design, and these [can be conflicting priorities] may conflict.	
5.2 Recommend changes in orbit	Med.	Requires consideration of multiple factors to determine if there will be an advantage to changing the orbit. (Anticipated launch/target sites, current orbit, threats to Airborne Laser, priorities, etc.)	The aircraft may already be in a right bank although you need to turn left. It may be quicker to keep turning right even though it is the longer route. Display aid – the system could help calculate and recommend orbit changes.
5.3 Know weapon status/Is the laser ready to shoot	Med.	Sensors may be deceiving, weapons status may not be readily apparent. Operators need a mental model of the system and affordances.	The system may determine there is not enough time and decide not to fire at the missile. If the system will not fire, the operators need to be informed of the reason why.
5.4 Know link status	Med.	Sensors may be deceiving. Operators need a mental model of the systems and affordances.	
5.5 Maintain mental model of system affordances and capabilities	Med.	Operators need to know what the system is capable of under different situations, be able to match situation to the capability.	

* CC stands for Cognitively Challenging

Table A-5. Readiness to Shoot (continued)

Decision/function	CC	Why challenging	Additional CTA data
5.6 Determine range from objects (i.e., how long until reach the end of orbit)	High	This requires time-space calculations that are difficult to perform mentally with great accuracy.	Display fix – Give operators the ability to click on a section of orbit to determine time to intercept. Be sure to specify miles or kilometers.

Table A-6. Decide Whether to Stop Shot

Decision/function	CC*	Why challenging	Additional CTA data
6.1 Deconflict missiles from aircraft and satellites	Med.	Currently requires integrating information from two displays multiple points of view.	Display aid – Even in manual mode, the system could provide a warning if a conflict is detected. Display aid – Have potential conflicts blink on the screen.
6.2 Maintain mental model of satellite locations (orbits, movements, speed, future locations)	High	The locations are constantly changing and information about location may not be easily obtained because of its classified nature. Requires a 3-dimensional model of the world to know if there are conflicts.	
6.3 Determine type of missile	High	Operators need to detect subtle cues because many missiles appear similar. In the case of modified missiles, there is no basis for comparison.	The highest priority are those missiles carrying weapons of mass destruction. How quickly can the system be updated? The type of missile affects prioritization. Need to be able to distinguish between SAMs and TBMs. The Airborne Laser's mission is to shoot down TBMs. The only time the Airborne Laser will shoot SAMs is in self defense. A history of missile origins as well as the type of missile would be helpful. A library of plume signals could aid the system in identifying the type of missile.

* CC stands for Cognitively Challenging

Table A-6. Decide Whether to Stop Shot (continued)

Decision/function	CC	Why challenging	Additional CTA data
6.4 Determine how many shots are left	High	This will vary depending on time required for each shot.	Depends on angle, distance, and altitude for shot. Unless the operator knows each of these, s/he can only estimate.
6.5 Ensure compliance with ROE	High	ROE can be ambiguous, poorly stated, and subject to interpretation	
6.6 Know tactics and strategies	Med.	Need to know when to apply the strategies. This is based on vast experience and declarative knowledge.	Possible reasons for no-kill: out of range, long missile, or bad angle.
6.7 Notice launch	Med.	Requires vigilance.	Display fix – Combine an audible warning with a flashing missile track.
6.8 Determine location of missile	Med.	It may be difficult to discriminate missile tracks from other tracks, especially if they are overlapping.	
6.9 Prioritize targets	High	Take multiple things into consideration, such as Battle Management Mode. There may be modified missiles for which there is incomplete information and no basis for comparison.	If the enemy has modified the missile it may be unfamiliar and not match anything in the database. The decision may have been made to shoot and then a higher-priority missile is launched. There could be conflicting inputs. Prioritization is based on: special instructions, ROE, dynamic environment (system operation, laser fuel, multiple operations, station time left, and guidance).

Table A-7. Adjustments during Engagement

Decision/function	CC*	Why challenging	Additional CTA data
7.1 Acquire target	Low	May be difficult to locate if there are other overlapping tracks in the area.	
7.2 Determine mode (manual, auto, semi)	Med.	Requires knowledge of capabilities of all modes to match the situational aspects to the appropriate mode.	The operator may want to be in manual if the system will not lock onto a track or to select another track (prioritize).
7.3 Assess whether the missile is at a good angle to shoot	Med.	Need to integrate information from multiple displays and perspectives.	If the missile is "facing" the Airborne Laser (coming directly towards the Airborne Laser), it is a non-optimal shot. It may be better to wait until the angle changes.
7.4 Determine if the missile is at a good altitude to shoot	Med.		If the target is coming straight at the Airborne Laser, it is a non-optimal shot. It may be better to wait until the missile trajectory changes.
7.5 Determine why the system won't engage	High	Need detailed knowledge of the system and no-shoot parameters. This information may not be apparent. If not obvious, there is no way to find out.	Display aid – the system could display "no fire" if a satellite is in the way.
7.6 Track missile progress/status	Low		
7.7 Gauge optical turbulence	High	Must be able to understand implications of varying degrees of turbulence.	The atmospheric model of the day could be success or failure oriented. May require a sophisticated display to "get a sense of" optical turbulence.
7.8 Judge time to hook, lock, engage	Med.	Space, time, movement, and speed integration required.	
7.9 Determine how long to wait to shoot	High	Involves risk assessment and tradeoffs.	The closer the missile, the higher the kill rate and the shorter the shot. However there is a higher risk of the missile burning out or dropping too low.

* CC stands for Cognitively Challenging

Table A-7. Adjustments during Engagement (continued)

Decision/function	CC	Why challenging	Additional CTA data
7.10 Determine how long to engage target	Med.	There are a limited number of shots per mission, completing goals, and resource allocation issues.	The longer the engagement, the more fuel is used.
7.11 Isolate missiles	Med.	Need to quickly manipulate the screen and zoom in to select one missile from a group of missiles.	Display fix – Provide a back button to easily zoom in and out between different magnifications.
7.12 Manipulate screen interface	Low		
7.13 Report results	Low		Display fix – display information on the screen for a longer period of time.

Table A-8. Deal with Emergency Situations

Decision/function	CC*	Why challenging	Additional CTA data
8.1 Decide whether to perform emergency landing	High	Must determine: is it safe, other alternatives, best location to land, and implications. May require mental simulation of potential events.	
8.2 Decide whether to perform fuel/chemical dump	High	Must determine: is it safe, other alternatives, and implications of actions. May require mental simulation of actions.	
8.3 Deal with chemical leak	High	Must determine: danger to crew members, danger to aircraft, how should the leak be dealt with, and severity of the leak.	
8.4 Determine danger to crew	High	Need a mental model of the laser and laser components in order to project into the future.	
8.5 Determine system status	High	This may be deceiving. Operators need to detect inconsistencies or violations of expectations.	
8.6 Monitor weather	High	Need to determine what is relevant, and how it will affect the mission, laser, and aircraft.	
8.7 Anticipate retrograding	Med.	Need to think ahead, assess threat to aircraft, determine range from threat, determine when it is too late to retrograde, and use this information to build an understanding or the world.	
8.8 Perform visual identification	Low		
8.9 Realize things are "not going right"	High	Must have a baseline for comparison to notice inconsistencies or violations of expectancies. There are many things that could go wrong (aircraft mechanics, laser, systems, enemy threats)	

* CC stands for Cognitively Challenging

Table A-8. Deal with Emergency Situations (continued)

Decision/function	CC	Why challenging	Additional CTA data
8.10 Recognize jamming	Med.	Need to be able to see what is not there and notice violations in expectancies.	
8.11 Apply techniques to reduce degradation from jamming	Med.	Involves troubleshooting, knowledge of the system and strategies, and the ability to think like the enemy.	

Table A-9. Keep the System Working

Decision/function	CC*	Why challenging	Additional CTA data
9.1 Prioritize which systems to troubleshoot	High	All the systems are necessary. May need to mentally simulate to determine which system is most critical. Must maintain a mental model of all the system functions to assess their effect on mission objectives.	If AWACS loses radar the Airborne Laser is vulnerable to attack. If the link to AWACS is down, the Airborne Laser can continue the mission but is dependent on AWACS for self-protection. If several systems go down, which one do you fix first?
9.2 Switch configurations between users	Low		
9.3 Apply strategies	Med.	Requires experience and knowledge to understand strategies and when to apply them. An abundance of technical knowledge is needed to monitor laser status.	If the link goes down, the Airborne Laser needs to turn away from the threat.
9.4 Calibrate and initialize computers	Low	May need to calibrate several systems at once.	
9.5 Maintain mental model of system and affordances	Med.-High	Need to know what the system is capable of under different situations and be able to match situation to the capability. Requires intimate understanding of the system.	
9.6 Maintain link	Med.	Troubleshooting involves noticing subtle cues, determining what is wrong, and applying strategies.	
9.7 Optimize the IR	Med.	This is difficult when sensor suites are degraded.	Resolution and resolve rate are lost and operator will need to decide what to ignore. This can be done by shrinking the field of regard.
9.8 Request data update	Low		
9.9 Determine how to work with degraded systems	Med.	Need to determine if the degradation is too severe to continue mission.	May have to develop workarounds or contingencies.

* CC stands for Cognitively Challenging

This page left blank intentionally.

Table A-10. Track Detection and Identification

Decision/function	CC*	Why challenging	Additional CTA data
10.1 Locate tracks by number	Low	There are multiple tracks and operators need to account for track number changes (which is an unlearning issue).	
10.2 Use standardized voice tell formats	Low	Requires declarative knowledge of voice tell formats.	
10.3 Highlight tracks	Low		
10.4 Accept/reject automatic identification recommendations	Med.	Requires detection of problems/errors using subtle cues.	
10.5 Find tracks	Med.	Must know bearing and range of tracks.	

* CC stands for Cognitively Challenging